THE APPLICABILITY OF RECYCLED WASTE PAPER AS LIGHTWEIGHT BUILDING MATERIALS

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ABSTRACT

In this era of increasing standard of living and rapid growth of civil engineering construction, environmental issues pertaining to natural resources depletion, global warming, energy crisis, waste pollution and greenhouse gas emission have been major issues of concern throughout the world and most especially in the construction industry. This research was conducted to investigate the applicability of recycled wastepaper as lightweight building materials with focus on contributing to sustainability in the creation of the built environment. The major aim was to develop an eco-friendly lightweight non-loadbearing block from recycled wastepaper without the use of cement as binder. This study specifically addressed the drawback of low strength development that usually occur with increasing wastepaper content in the existing cement-based-wastepaper blocks. It also indirectly addresses; the environmental impacts associated with the construction industry (including; high consumption of natural resources, greenhouse gas emission, high energy consumption and so on), the environmental pollution resulting from unsustainable waste generation, and the generic drawback of high water absorption that plagues wastepaper-based blocks. To achieve this, research methods including; laboratory experimentation and simulation modelling were employed. The research outcome is an eco-friendly block unit designated as Cement-less Wastepaper-based Lightweight Block (CWLB) which contains 75% waste content and exhibiting properties that satisfy the requirements for application as non-loadbearing lightweight blocks in building construction. CWLB displayed compressive strength that far outweighs those recorded for the existing cement-based wastepaper blocks available in the literature. The properties recorded for the optimal CWLB includes; 2.71 MPa average compressive strength, 901.5 kg/m^3 average density, 0.19 W/m.k thermal conductivity, 989.9 m/s ultrasonic pulse velocity, 0.0026 $g/m^2.S^{0.5}$ average coefficient of capillary water absorption and 883.38 MPa estimated elastic modulus. The approximate compressive strength of 2.38 MPa and 1.58 MPa were respectively predicted and recorded for the solid and hollow finite element model samples of CWLB. The impressive satisfactory properties of CWLB for the intended application and its eco-friendliness in terms of natural resources conservation and improved compressive strength suggests that CWLB shall indeed serve as a more sustainable alternative to the reigning/existing cement-based-wastepaper blocks and to the conventional masonry blocks of the same category. Amongst other things, future work will address the validation of the approximate compressive strength predicted for the solid and hollow CWLB insitu samples in order to take further the subject matter.

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DEDICATION

To the Almighty God, my present and continuous help at all times, my shield and the lifter of my head.

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CHAPTER ONE: INTRODUCTION

1.1 BACKGROUND

Environmental pollution resulting from industrial and domestic waste material is one of the biggest problems facing the human race and much concerted effort is being put into solving this problem on a worldwide basis (Wilson and Rogero, 2015; United Nation Environmental Programme (UNEP), 2015). Presently, municipal solid waste (MSW) is growing faster than the rate of urbanization. The global urban per-capital municipal solid waste (MSW) generation increased from 0.64 kg/day in 2002 to 1.2 kg/day in 2012 (Hoornweg and Bhada-Tata, 2012). This means that the world experienced an estimated total of 87.5% increase in waste generation per person per day within that ten-year period. A comparison of this statistics with an estimated 3.45% corresponding global urban resident population increase (within the same period) indicate the level of unsustainability of waste generation occurring in this present day and age. The forecast of a possible increase of this MSW generation to 1.42 kg/capital/day by 2025 (Hoornweg and Bhada-Tata, 2012) is also of concern. To solve this problem effectively, there is need to establish a more holistic solution for the recycling of waste material safely at low cost and in an environmentally friendly manner.

Recycling as a means of waste disposal has received considerable attention all over the world; it is a key component of the modern waste reduction and the third component of the "reduce, reuse and recycle" waste hierarchy. The United States Environmental Protection Agency (US EPA) (2014a) defines recycling as the process of collecting and processing materials that would otherwise be thrown away as trash and turning them into new products. It possesses numerous benefit for the environment in that, it reduces the amount of waste that goes into landfills and incinerators, conserves natural resources, prevent pollution by reducing the need to collect new raw materials, saves energy, reduces greenhouse gas (GHG) emissions, helps sustain the environment for future generations and enhance the creation of new jobs in the recycling and manufacturing industries (United States, Office of Resource Conservation and Recovery, 2015).

On the other hand, the environmental impacts associated with the activities of the construction industry have designated it as one of the major sectors that comes to mind when the subject of environmental sustainability is being discussed. The European commission (2013) considers two of such impact to be high consumption of natural resources and high generation of waste. According to the same source, the construction industry is responsible for the consumption of over 50% of all material extracted from the earth and generation of over 450 million tonnes/year of waste in Europe (European Commission, 2013). Also, most conventional building materials such as; aggregate, cement and concrete are usually obtained and/or produced from natural resources. From literature evidences, apart from the notable impacts (including; GHG, CO_2 emission and excessive raw material consumption (Oss and Padovani, 2003)) that are associated with the manufacturing of cement, the production of concrete is also highly material intensive. The United States Geological Survey (USGS) reports that the building industry requires about six to seven more tonnes of sand and gravel, for each tonnes of cement used in construction (USGS, 2013). These impacts along with the future impacts that will result from the ever increasing expected/forecasted rapid growth of global construction by the year 2025 (Global Construction Perspectives and Oxford Economics (GCPOE) forecasts, 2013) and the year 2030 (GCPOE forecasts, 2015) are gradually making the creation of the built environment to constitute a rising hazard to the natural eco-system. Presently, the natural resource base of the world is said to be in a state of overexploitation and depletion (Giljum *et al*., 2009). At the global level, sand and gravel are reported to account for 68% to 85% of about 59 billion tonnes of material mined from the earth every year (United Nations Environment Programme - Global Environmental Alert Services (UNEP GEAS), 2014; Steinberger *et al*., 2010; Krausmann *et al*., 2009). The 25.9 to 29.6 billion estimated world consumption of aggregate for concrete in 2012 alone was said to represent sufficient quantity of concrete that can be used to construct a 27 meter high by 27 meter wide wall around the equator (UNEP GEAS, 2014). The world over 40 billion tonnes annual aggregate consumption has been estimated to be about 100% higher than the yearly aggregate renewal by all rivers of the world (UNEP GEAS, 2014). Therefore, these impacts and their consequences calls for an urgent mitigation measure to achieve sustainability in the construction industry.

As awareness of the potential environmental impacts of building construction has grown, efforts are being made to avoid these adverse effects and to work towards impact mitigation. One of such efforts in the European commission is the establishment and funding of "Eco-innovative" which is an initiative saddled with the responsibility of encouraging the use of:

- Environmentally-friendly construction materials and innovative manufacturing processes;

- Construction products and related processes that reduce consumption of resources, embodied carbon and production of by-product wastes.

Also, some other cautiously suggested approach to achieve sustainability in the construction industry includes; the use of fewer natural resources, less energy and minimised carbon dioxide emissions in order to produce an environmentally friendly concrete (Mehta, 2002). In addition, a decrease in the amount of calcined materials in cement, reduction in the amount of cement in concrete and decrease in the number of buildings using cement (McCaffrey, 2002). The Eco Innovative under the European Commission also encourages the design of innovative products using recycled material (European Commission, 2013).

The productive use of waste material represents a means of reducing some of the environmental impacts associated with the activities of the construction industry; the implementation of such approach minimizes the use of natural resources and in some cases result in the production of environmental friendly products. The need for safe and economic disposal of waste material is part of the reasons for the continuous advancement of research into the innovative use of waste materials in construction. Clean environment, reduced use of natural resources and dumping spaces are the benefits that could be achieved through the use of recycled waste materials such as recycled aggregates, recycled glass, recycled paper, recycled plastic, recycled metal, recycled textile and recycled fibre in building materials.

Among the various components of MSW is paper and paper products. It is one of the most important products ever invented by man, and it made possible the widespread usage of written language throughout the whole world. Paper can be described as a sheet of cellulose fibre mostly obtained from wood, rags or grass fibre and sometimes other plants such as cotton, rice and papyrus can be used for the production of special papers. Ever since its invention, it has formed an important part of human day to day activities. The versatile properties of wastepaper (such as: stiffness, toughness, lightweight, etc (Levlin, 1999; Levlin and Söderhjelm, 1999) have enabled its usage in many applications including; writing and printing upon, cleaning products, packaging material, industrial and construction purposes (Teschke, 2011)

The need to utilize wastepaper for purposes other than recycled paper production is paramount considering two major reasons viz, its considerable availability in the worldwide municipal waste stream and the consequences that could result from its inappropriate disposal. Judging from the literature evidence regarding wastepaper availability, it appears that, the more it is being utilized for several applications, the more the amount being generated and the higher the percentages that find their way to the municipal solid waste stream. Wastepaper represents 25 to 40% of worldwide MSW each year (Grigoriou, 2003). According to the US EPA Office of Solid Waste and Emergency Response (US EPA OSWER), paper and paperboard products make up the largest portion of the municipal solid waste stream in the United States, occupying 34% of the MSW composition in 2005 (US EPA OSWER, 2008) and 27.3% of the total MSW before recycling in 2012 (US EPA, 2014b). Similarly, paper and cardboard waste forms the largest fraction of the municipal waste stream in Europe, accounting for 41% of the over 79 million tonnes of packaging waste generated in 2013 (Eurostat Statistics Explained, 2016). The organic characteristic of wastepaper which gives it the potential to decompose and release methane in the landfill constitute a hazardous impact that could result from its inappropriate disposal. Wastepaper therefore represents a considerable environmental and social problem, whose recycling can reduce pollution, conserve landfill spaces (required for its disposal), and enhance its productive use for several eco-friendly purposes (including; fuel, building insulation, building materials, potting mixture, insulation in cars and shoes) aside it uses for paper and card production.

It is also interesting to note that despite the advent of computer and the various prediction and campaign for reduction in paper usage, the demand for paper keeps increasing even at a rate faster than the global population growth. As an evidence, compilation of global paper consumption records from the literature (Hoornweg and Bhada-Tata, 2012; The statistics portal, 2014) shows that between the year 2009 and 2012, the world experienced 5.5% increase in per-capital paper consumption at a corresponding 0.0037% increase in global population. Similarly, previous evidence of 2.5% steady annual increase in paper production rate was also reported to have occurred between 1980 and 1993 with a worldwide production record of 400million tonnes in 1993 (Canadian Pulp and Paper Association, 1995).

Thus, the increasing rate of global per-capital paper consumption and the prediction of a possible increase of global paper production from the present 450 million tons per year to 500 million tons by 2020 (Ali *et al.*, 2013) are indications that monopolizing the recycling of wastepaper to paper production alone is not enough to solve the enormous quantity of wastepaper generation. A proof of this is the amount of waste paper that are still going into landfill and incineration, despite the high recycling rate achieved in few developed countries. For instance, an estimated volume of 10 million tonnes of paper and board which could have been recycled is still currently going into incineration and landfill in Europe, despite the 71.7% recycling rate achieved in 2012 (Confederation of European paper Industries (CEPI), 2014), 48 million tonnes is being disposed in USA (Nepal and Aggarwal, 2014) despite the 65.8% recycling rate.

Similarly, in Nigeria, as a result of inadequate means of collection and disposal of wastepaper (including old newspapers), a considerable amount get disposed on open dumpsite, get burnt, incinerated, and some are being indiscriminately disposed. This is consequence upon the large newspaper market available in Nigeria. In 2012, Nigeria was said to have the second largest market of newspaper in Africa after Egypt (Obohwemu, 2014). Nigeria is said to possess over 278 newspaper publishing companies, most of which release an average of about 10,000 to 20,000 copies into circulation daily and weekly (Nigerian press council, 2015). For that reason, large amounts of postconsumer newspapers have accumulated in many places over the years, as a result of continuous daily and weekly circulation all year round. Old newsprints are either kept in the house or aimlessly disposed after reading.

Therefore, in an attempt to address these problems and following the various cautious suggestions on means of achieving sustainability in the construction industry, a lot of researchers, Akinwumi *et al.*, 2014; Aigbomian and Fan, 2013; Briga-Sá *et al.*, 2013; Turgut and Yahlizade, 2009; Marzouk *et al.*, 2007; Park *et al.*, 2004; Zavala, 2013 etc have investigated the use of solid waste material, such as plastics, wood, textile, glass and paper, in production of building materials. Particularly, waste paper have been utilized for purposes such as, fibre cement board (Ashori *et al.*, 2011), block (Modry, 2001; Fuller *et al.*, 2006a; Akinwumi *et al.*, 2014), low density board (Esmeralda *et al.*, 2000), papercrete (Fuller et al., 2006a; Fuller et al 2006b), brick (Jegatheeswaran, 2011), plastering mortar (Aciu *et al.*, 2014).

However, extensive literature review has shown that, building material produced from waste paper suffers high water absorption, thickness swelling and low strength with increasing paper fibre content (Akinwumi *et al.*, 2014; Aciu *et al.*, 2014; Zavala, 2013; Ashori *et al.*, 2011; Yun *et al.*, 2007; Tizman, 2006; Decard *et al.*, 2001). The approach of previous research to solve this low strength constraint has led to the utilization of considerable quantity of cement in a bid to improve the strength properties of waste paper based building materials (Zavala, 2013; Brock, 2011). Also, considering the impacts associated with cement production, the high percentage of cement being utilized in the constituent of some wastepaper-cement-based building materials is believed to be undermining their environmental friendliness. It is therefore paramount to investigate the production of a more eco-friendly wastepaper-based building material without the use of the controversial hydraulic binder or Portland cement.

1.2 PROBLEM STATEMENT

The notable environmental impact of the construction industry has become an issue of global concern. The natural resource base of the world is in severe danger of overexploitation and collapse due to the continued high level of resource consumption and industrialization (Giljum *et al.*, 2009). This indicates the need to conserve scarce and expensive resources especially those being utilized in construction. At the global level, the construction industry is said to be responsible for enormous raw material consumption in the range of 40% (United States Green Building Council (USGBC), 2004; Lenssen and Roodman, 1995) to 60% (Hawken *et al.*, 1999) of the total available to the world. A similar estimate is applicable to other major resources including; water, energy, and land use. In Europe, housing and infrastructure are regarded as one of the most resource-intensive areas of life accounting for 31% of resource consumption (Giljum *et al.*, 2009). In the UK, the construction industry is regarded as the largest consumer of natural resources with over 400million tonnes of material consumed each year (WRAP, 2007). The construction industry is also said to be responsible for 10% of the total UK Carbon emission (UNEP SBCI, 2009)

In the USA, building structures which are the major product of the construction industry are said to be responsible for the following; the use of 70% of total electricity (U.S. Energy Information Administration (EIA, 2001) with over 39% consumption of energy (EIA, 2001), emission of 39% of the greenhouse gas emissions (EIA, 2003), production of 136 million tons of construction and demolition wastes (US EPA, 1998), utilization of 11% of potable water (USGS, 2000). Also, the Portland Cement Association in the United States estimated that, the construction Industry consumed 80% of cement produced in 2003 with building accounting for 47% and streets and highway accounts for the remaining 33% (US EPA, Office of Resource Conservation and Recovery, 2009).

The present rate of waste generation is unsustainable and there are predictions that suggest the continuous occurrence of same in the nearest future. The global MSW generation is said to be growing at a rate that could initiate the occurrence of tsunami of waste if adequate mitigation measure are not put in place. The global rate of paper consumption indicates a continuous availability of wastepaper beyond the quantity that can be monopolized for recycled paper production alone. Literature evidence shows that paper consumption is a function of rises in the GDP of a country and countries income level (Kinsella *et al.*, 2007); this suggests that the demand and consumption of paper may represent a permanent issue in human day to activities. Therefore, the earlier a holistic approach is taken to manage the availability of waste paper in the environment the better for the achievement of sustainability.

The need for alternative building materials, which can be used as a partial or full replacement of both cement and also aggregates, which are considered the main ingredients used in the manufacturing of blocks can also be justified based on the fact that many countries around the world are beginning to experience increasing price of most conventional building materials. The global demand for construction minerals was said to have increased rapidly by 80% from 1980 to 2008 (Organisation for Economic Co-operation and Development (OECD), 2013) and in some countries, there has being a general scarcity of natural materials that are suitable for construction. In recent years, there has been an increase in the consumption of raw materials in the construction industry at a rate far exceeding their replacement (UNEP GEAS, 2014). Also, the expected increase in construction volume (GCPOE forecasts, 2013) at some designated developing countries calls for urgent development of alternative building materials to prevent the occurrence of past cases of overconsumption of natural resources associated with the development of some developed countries.

Recycling as a method of waste disposal is not yet receiving adequate attention in Africa, Nigeria inclusive. While developed regions such as Europe and the United states are looking forward to a zero waste environment by the year 2020, according to the World bank report on municipal solid waste statistics, as at 2012, only 4% of the total waste generated in Africa is being recycled while Nigeria falls in the category of countries where only 1% of the total waste generation is being recycled. Literature evidence shows that in Nigeria, only 30% of the urban solid waste generated is being collected and adequately disposed (Ogwueleka, 2009). The uncollected portion accumulates in various places such as on the housing compounds or on open spaces, on streets, and thrown in ditches. Such inadequately disposed waste pollutes the surface and in many cases directly enters into the storm water drains or river streams. In other situations, people throw waste directly into the storm water drains and streams which not only pollutes the water but also clogs drainage and increases the risk of flooding (Babalola *et al*., 2010). This is consequent upon the defective strategies adopted for solid waste management which is obviously based on the fact that the rate of collection and evacuation is very much below the rate of generation and thereby resulting in waste accumulation which is now a major environmental issue in the country. The implementation of recycled use of waste in construction will apparently encourage recycling of wastes and represent a cost effective way of waste management in such developing economy.

In view of the aforementioned problem statements and the drawbacks associated with wastepaper based building materials, this research seeks to investigate the possibility of using wastepaper for the production of lightweight non-loadbearing block without the use of hydraulic binder, and with properties suitable for use as a building material in construction in Nigeria and all other applicable places.

1.3 AIM AND OBJECTIVES OF THE STUDY

The aim of this research is to produce an environmental friendly lightweight non-loadbearing block from recycled waste paper without the use of hydraulic binder and with property suitable for use as walling unit in building construction. The proposed block is designated as cement-less wastepaper-based lightweight block (CWLB).

The main objectives are to:

- Conduct a literature review on the state of the art.
- Develop a mix proportioning process for the production of the cement-less wastepaper-based lightweight block (CWLB).
- Identify and study the salient parameters that affects the strength properties of CWLB
- Determine the optimum mix composition for CWLB.

- Study the engineering properties of CWLB in accordance with relevant standards.
- Explore the possibility of using waste lactose (a waste by-product of dairy industry) as binder for the production of CWLB.
- Carry out simulation modelling of the compressive strength of a typical representative insitu sample of CWLB in order to assess its real life compressive loading capability.
- Provide deliverables including; a suitable energy efficient manufacturing technology for CWLB, a systematic energy efficient manufacturing technology for granular wastepaper aggregate (WPA), evidence based information on peculiar behaviour of CWLB, optimum mix composition of CWLB, engineering properties of CWLB (viz: Compressive strength, Density, Ultrasonic pulse velocity, Elastic modulus, thermal conductivity, coefficient of capillary water absorption) and the approximate compressive strength of CWLB insitu solid and hollow finite element model samples.

1.3.1 Research Questions

The research questions that this study seeks to answer includes:

1) What mixture proportioning process is required to produce CWLB?

2) What will be the outcome of using a non-hydraulic binder?

3) What other salient parameters will affect the properties of CWLB?

4) What are the engineering properties that CWLB will exhibit?

5) How will a typical insitu sample of CWLB unit react to application of loading in practical situation?

1.4 SCOPE OF THE STUDY

This research is limited to the use of post-consumer waste paper (old newsprint) and fine aggregate (sand) as filler materials in the lightweight block production. Waste lactose which is a waste byproduct of the dairy industry was utilised as binder. Small quantity of natural admixture was applied as required. In order to assess the efficiency of the block as a walling unit material, its engineering properties were investigated.

As much as possible, the available Standards required for conventional non-load bearing masonry block were used as a guideline to ascertain the properties of the proposed block. The technology and the equipment currently available for the manufacturing of masonry block was employed as much as applicable for the production of the proposed cement-less wastepaper based lightweight block.

Every relevant test materials including wastepaper, sand, admixture (stoneware clay), waste lactose and other equipment with energy conservative characteristics were obtained from the United Kingdom.

1.5 SIGNIFICANCE OF THE STUDY

Recycling and reuse of waste material is a viable waste reduction strategy that enables the recycled or direct utilization of such wastes for the production products. It implementation brings about the benefit of producing usable materials with significant conservation of natural resources.

The CWLB being developed in this research may be an eco-friendly alternative to the conventional non-loadbearing masonry blocks that are commonly being utilized in the construction industry (especially in Nigeria) whose production requires the usage of about 86% aggregate in combination with 14% Portland cement.

The success of this study may also contribute to the preservation of the environment from being polluted by inadequate disposal of waste paper through open dumping and burning. It may also bring about reduction in the landfill space required for the disposal of waste paper

The success of this research could also bring about an advancement in recycling technology in Nigeria and at the same time be an eye opener for the Nigerian Government to invest in recycling of waste and thereby make appropriate legislation (just like in Europe and USA) coupled with incentives in order to encourage the general public to participate in recycling.

Natural resource conservation can also be achieved considering the utilization of high waste content in the production of the block. For instance, CWLB contains 75% waste content in its mix composition, this indicates reduction in environmental pollution resulting from the said wastes (in this case, wastepaper and dairy wastes) and less consumption of natural resources.

This study also brings about the promotion of the practice of industrial ecology, considering the utilization of waste lactose as binder, thereby solving the environmental and economic impact associated with its disposal.

The expected lightweight characteristic of the blocks also indicates less construction cost and less construction time, this indicates indirect solution to housing problem in developing and developed countries for both the government and low-income earners.

The methodology developed in this study could serve as a basis for the production of alternative eco-friendly blocks from similar waste materials in the future. Therefore, the significance of this research is in the area of sustainable development in the built environment, reduction of environmental pollution caused by the disposal of solid waste (in this case wastepaper), natural resources conservation, cost of construction, and sustainability of the environment.

1.6 CONTRIBUTIONS TO KNOWLEDGE

The findings/outcome of this research will be a significant basis for the production of alternative/affordable building material in Nigeria with less use of natural resources. Therefore, it is believed that at the end of this research, the following inputs/know-hows have been contributed to the body of knowledge:

- Development of the mixture proportioning process/manufacturing technology for the proposed novel CWLB
- Development of manufacturing technology for processing of wastepaper into an artificial aggregate
- Development of optimum mix composition for CWLB
- Determination of the peculiar behaviour or otherwise of CWLB
- Determination of the engineering properties of CWLB

- Simulation modelling of the compressive response of the CWLB in real life application

It is also expected that the outcome of this research would prompt sustainable development in the built environment (in countries where construction boom is being expected in the nearest future) through the production of an eco-friendly alternative non-loadbearing block compared to the cement-based-natural-resources-intensive non-loadbearing blocks commonly being employed in building construction. Considering that most developing countries like Nigeria are so attached to the tradition of using masonry/sandcrete block for non-structural wall, the availability of the CWLB in similar shape, sizes, and strength which they are familiar with and at a low cost, low weight and reduced construction period may encourage prospective building owners to accept and apply it as an eco-friendly alternative in future construction.

1.7 RESEARCH METHODOLOGY APPROACH

The methodology approaches employed in this research to achieve the objectives of the study are:

- Literature review
- Laboratory experimentation
- Simulation Modelling

1.7.1 Literature Review

Extensive literature review was used to establish the necessary theoretical framework and the state of the art gaps in knowledge in order to scope the research.

1.7.2 Laboratory Experimentation

Laboratory experimentation was used to;

i) Develop a standard mix proportion for the CWLB,

ii) Explore the possibility of making use of non-hydraulic binder for the production of CWLB,

iii) Test the various engineering properties of CWLB through experimental examination in accordance with relevant standards.

1.7.3 Simulation Modelling

Finite element simulation modelling approach with the aid of Abaqus CAE version 6.13 software was used to investigate the real life/approximate compressive response and loading capability of a typical CWLB finite element insitu model sample using parameters obtained from laboratory experimental investigation as input.

1.8 RESEARCH DISSEMINATION

The research idea and findings were disseminated through presentations of research papers at international conferences and publication in academic Journals.

1.8.1 Published Papers

The bibliographic details for already published papers are listed below:

i. Okeyinka O.M., Oloke D.A., Khatib J.M. (2016) Salient Parameters Influencing the Strength Properties of Cement-Less Wastepaper Based

Lightweight Block. *Fourth International Conference on Sustainable Construction Materials and Technologies* (*SCMT4)* [online]. University of Nevada, Nevada, Las Vegas 7-11 August.
Available at: < http://www.claisse.info/2016%20papers/S147.pdf >.

ii. Okeyinka O.M., Oloke D.A., Khatib J.M., (2015) The use of solid waste materials in the production of building materials: A review*. International Conference on Sustainable Building and Architectural Engineering (ICSDEC 2015)* [online], France. 30-31 December. Available at: http://waset.org/publications/10003128/a-review-on-recycled-use-of-solid-wastes-in-building-materials.

iii. Okeyinka O.M., Oloke D.A., Khatib J.M., (2015) A review of recycle use of post-consumer waste paper in construction. *1st International Conference on Bio-based Building Materials (ICBBM 2015),* Eds. Amziane & Sonebi, 21-24 June 2015, Claremont-Ferrand, France*.* RILEM publication, pp. 711-717, ISBN PRO 99: 978-2-35158-154-4.

iv. Okeyinka O.M., Oloke D.A., Khatib J.M., (2015) Development of Environmental friendly lightweight building block. *2nd International Sustainable Building Symposium (ISBS 2015)*, Gazi University 28-30 May, 2015, Ankara, Turkey.

v. Okeyinka O.M., Oloke D.A., Khatib J.M., (2014) Waste paper A resource for sustainability in the construction Industry. *3^{rd} International Workshop on*

Earthquake and Sustainable Materials (IWESM,2014), Eskisehir, Turkey, 24th June 2014, pp. 133-144

1.8.2 Submitted Papers

The bibliographic details for submitted papers are listed below :

i. Development of an Eco-Friendly Lightweight Block from Post Consumer Wastepaper. Journal of Materials in Civil Engineering, American Society of Civil Engineering.

ii. Optimisation of Mix Composition of Cement-less Wastepaper-based Lightweight Block (CWLB). 8th International Conference on Civil Engineering (ECCIE' 17), 26-28 April 2017, Venice Italy.

iii. Characteristics of the Fresh Mixture of a Novel Cement-less Wastepaper-based Lightweight Block (CWLB) and Its Molding Processes. 9th Biennial International Structural Engineering and Construction Conference (ISEC-9), 24-29 July 2017, Valencia Spain.

1.9 THESIS ORGANIZATION

The thesis structure and the programme of research are presented in Figs. 1.1 and 1.2 respectively. The specific chapter descriptions are as follows:

Chapter One

This chapter provides background information for this research. It explains the motivation and the rationale for undertaken this research as well as its significance to the construction industry. Research aims and objectives, research questions, scope, and the method adopted were highlighted.

Chapter Two

This chapter builds a theoretical foundation for the research by reviewing literature and previous research efforts on the relevant subjects. It comprises of two major sections. The first section discusses the environmental impacts of the construction industry, the need for sustainability in the construction industry, recycling in construction, the use of recycled solid wastes in building materials and the recycled use of wastepaper in construction. Whilst the second section focuses on the broader discussion of recycling and building materials. It presents review on conventional masonry blocks, properties of wastepaper-cement-based blocks, drawbacks of wastepaper-cement-based blocks, summary of literature review, identified research gaps and the need for this research.

Chapter Three

Building on the review of literature in Chapters 2, this chapter provides an outline of the investigative research methodology aspects adopted for undertaking this research, which includes laboratory experimentation and modelling.

Chapter Four

This chapter presents and discusses the result of the findings of preliminary laboratory experimentation; it entails the process employed in the determination of mix proportioning process for the CWLB block being developed.

Chapter Five

This chapter presents and discusses the result of the findings from salient parameter studies and the studies conducted through experimentation to determine the optimum mix composition for CWLB.

Chapter Six

This chapter presents and discusses the comparative study of the other engineering properties of CWLB and the engineering properties of SWLB.

Chapter Seven

This chapter presents and discusses the details of the simulation modelling of the compressive load response of CWLB insitu solid and hollow finite element model samples conducted with aid of Abaqus CAE version 6.13 software.

Chapter Eight

This chapter presents the summary of the whole research, the conclusions drawn and recommendations made based on the laboratory experimental results and outcome of modelling. It also highlights areas of possible future work that can add value to the subject matter.

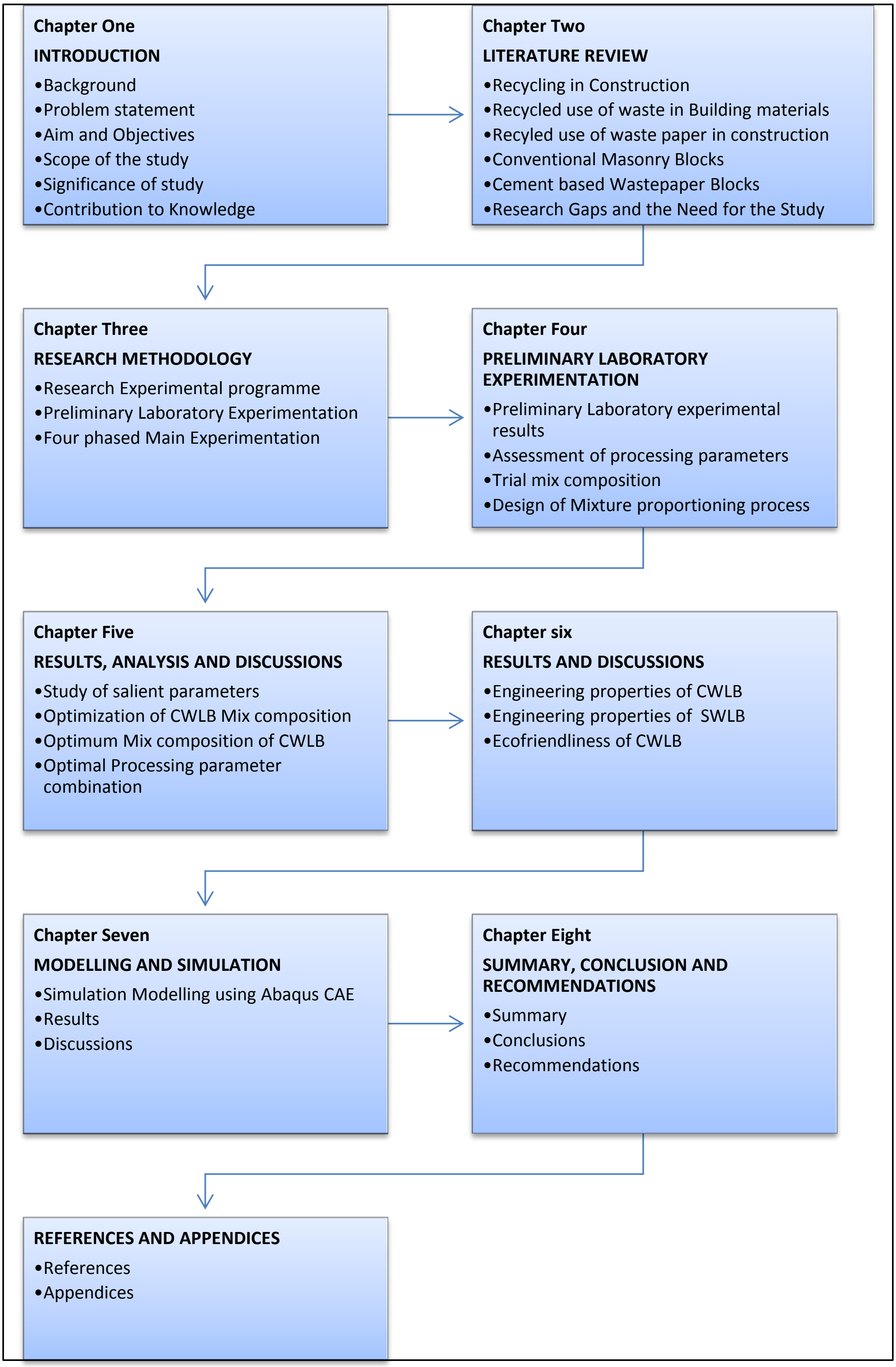


Fig. 1.1: Thesis structure

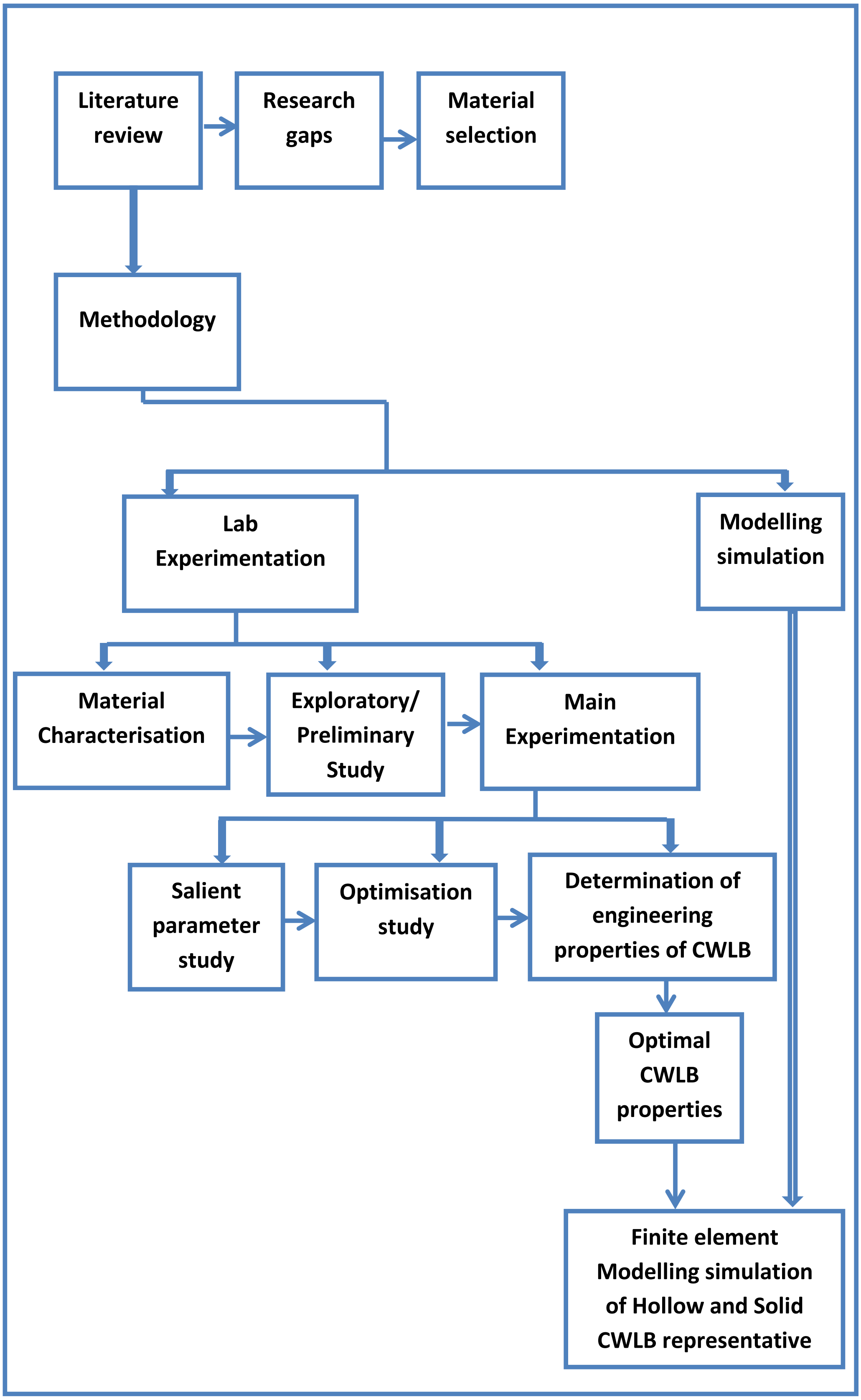


Fig. 1.2: Programme of Research

CHAPTER TWO: LITERATURE REVIEW

2.1 INTRODUCTION

This chapter presents the review of literatures that established a theoretical framework for the research and justified the research needs. The first section of the review (viz; 2.2 to 2.7) focuses on the subject of recycling in construction and related topics. This includes; unsustainable waste generation, environmental impacts of the construction industry, suggested approaches for achieving sustainability in the built environment, wastepaper availability etc. On the other hand, the second section (viz; 2.8 to 2.15) focuses on the conventional masonry blocks including; its fundamentals, technicalities of its manufacturing technology, previous use of solid wastes for its production etc. This chapter was finally concluded with a cumulative summary of both section of the literature review, the identified research gaps and the need for the present study.

2.2 RECYCLING IN CONSTRUCTION

Globally, recycling is regarded as the third most preferred waste disposal option (Fig. 2.1) (Hoornweg and Bhada-Tata, 2012). It is a key component of the 3Rs recommended for all countries of the world to address the increasing rate of waste generation. Contrary to critics about the environmental benefits of recycling, a review and analysis of several life cycle assessments (LCA) of recyclable wastes such as paper, cardboard, glass, plastics, aluminium, steel, wood and aggregate, have revealed and confirmed that recycling stands as the most viable waste disposal option (or waste management option) capable of offering environmental benefits and reducing environmental impacts, compared to other waste management options (Waste & Resources Action Programme (WRAP), 2010).

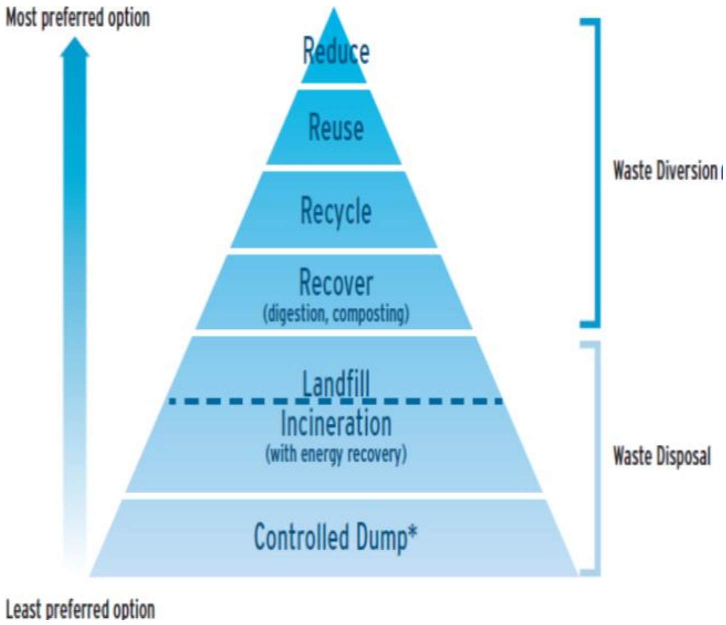


Fig. 2.1: Waste Hierarchy (Source: Hoornweg and Bhada-Tata, 2012)

Therefore, considering the various aforementioned benefits of recycling (as mentioned in Chapter 1), its implementation in construction appears to be a round peg in a round hole to address the issues of concerns associated with the activities of the construction industry

2.3 THE NEED FOR RECYCLING IN CONSTRUCTION

The need to employ the use of recycling in construction is paramount, considering the increasing/unsustainable rate of waste generation occurring worldwide (Fig. 2.2) and the environmental impacts associated with activities of the building construction industry. Other indirect reasons that necessitates the urgent need to implement the recycled use of waste in construction includes; the expected tremendous increase in the volume of construction in the nearest future (Global Construction Perspectives and Oxford Economics (GCPOE) forecasts, 2015; 2013) and the expected increase in urban population growth which may increase housing need in the future. According to a United nation report, the world population and urbanization are expected to increase by 2.5 billion by the year 2050, 90% of which is expected to be contributed by Asia and Africa (United Nations, Department of Economic and Social Affairs, Population Division, 2014). Also, due to the continuous increase in the world urbanisation, challenges relating to sustainable development are expected to be on the high side especially in cities located in lower middle-income countries (United Nations, Department of Economic and Social Affairs, Population Division, 2014).

2.3.1 The Unsustainable Rate of Global Waste Generation

Speaking of waste generation, the increasing standard of living and growth of civilization have prompted remarkable growth in the rate of waste generation over the past years, according to the UNEP GWMO report (2015), the trend of waste generation in some selected countries over a period of 50 years indicated a trend of an increasing waste generation with increasing income level (Modak *et al.*, 2015). Also, the world bank review on global solid waste generation (as illustrated in Fig. 2.2) indicated an excessive growth in global per-capital waste generation at a rate faster than the global urban population growth as well as the futuristic occurrence of same by the 2025 (Hoornweg and Bhada-Tata, 2012).

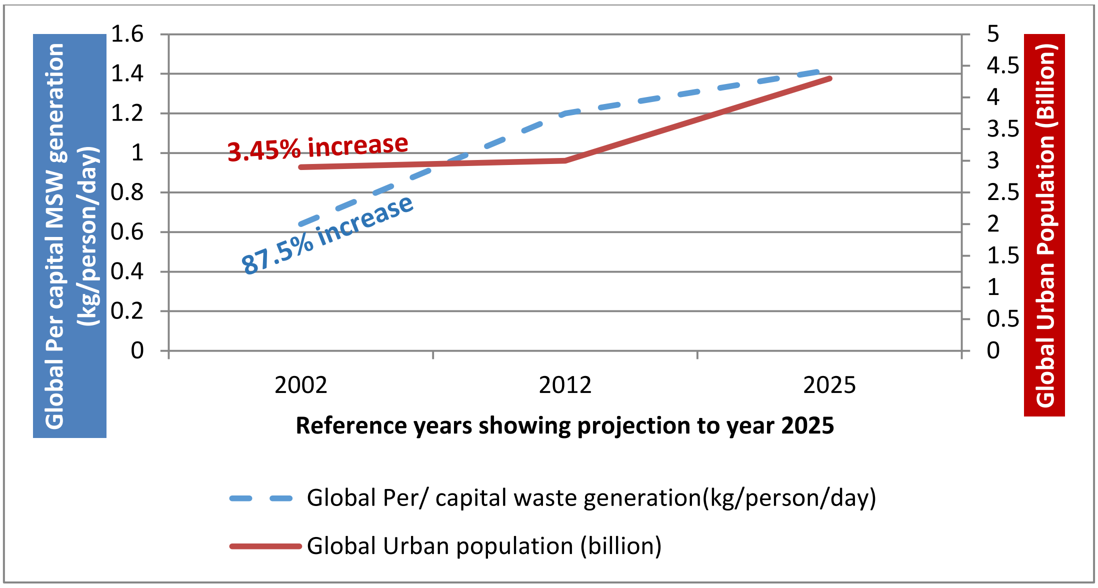


Fig. 2.2: Evidence of Unsustainable Rate of Global Solid Waste Generation and Evidence of Expected Unsustainable Growth in Global Waste Generation by 2025 (Source:Modified using information obtained from World bank report (Hoornweg and Bhada-Tata, 2012))

Therefore, the practice of recycled use of waste in construction will apparently provide solution to the problem of waste disposal and at the same time address the various world environmental concerns including; high consumption of natural resources, greenhouse gas emission, high energy utilization, pollution, etc.

A practical example of the extent of environmental benefit that could be achieved through recycling is found in the Stanford University's recycling and solid waste report (2011) (as illustrated Table 2.1). The reported impact reduction as calculated by the national recycling coallation's environmental benefit calculator revealed that, recycling of wastes like paper, glass, metals, plastic and organic wastes materials resulted in the conservation of 57951 million BTUs of energy (sufficient to power 551 homes for one year), reduction in air emission by 4579 tons, reduction in GHG by 3820 metric tons of carbon equivalent (MTCE), reduction in water borne waste by 17tons.

Table 2.1: Practical Example of Impact reduction and Environmental benefit Obtainable from Waste recycling (Source: Stanford University's recycling and Solid waste report, 2011)

Recycled wastes	Impact reduction	Natural resources conservation
Paper, glass, metals, plastics, and organic materials	Air emission reduced by 4579 tons.	57951 million BTUs of energy (enough to power 551 homes for one year)
	Water borne waste reduced by 17 tons	Not reported
	GHG reduced by 3820 metric tons of carbon equivalent (MTCE)	Not reported
1338 tons of paper	Not reported	32115 tree conservation
206 tons of ferrous scrap metals	Not reported	414 tons of iron ore, coal and limestone conservation

2.3.2 The Construction Industry

The immense contributions of the construction industry in the area of infrastructure, habitation and transportation have greatly prompted the development of civilization, economic progress and stability of the quality of life. Its products/creations make available the inevitable public infrastructure and private physical structures for productive activities which includes; services, commerce, utilities etc.

At the global level, speculations have indicated expected enormous growth in construction volume in the nearest future. According to a recent GCPOE (2015) forecasts "Global Construction 2030", the volume of construction output is expected to grow by 85% to $15.5 trillion worldwide by 2030. This present forecast represents a 15% increase compared to the previous speculation which predicted over 70% growth in global construction volume by 2025 (GCPOE, 2013). The forecast also speculate that remarkable contribution to the global construction volume will come from developed countries which are recuperating from economic instability and emerging countries that are currently industrializing and thereby resulting in a projected 3.9% growth in construction volume on a yearly basis up to 2030.

There are however few major drawbacks with respect to sustainability, two of such impacts as identified by the European commission (2013) includes; high consumption of natural resources and high generation of waste, (European commission, 2013). Other drawbacks include; greenhouse gas emission and energy usage (Hawken *et al.*, 1999; Brown and Bardi, 2001; EIA, 2003; EIA, 2001), external and internal pollution, environmental damage and resource depletion (Confederation of International Contractors' Associations (CICA), 2002).

Therefore, for the industry to operate according to the definition of sustainability as stated by the World commission on environment (1987), a balance needs to be maintained between the development brought about by the construction industry and the sustainability of the environment. To achieve this, various cautious suggestions have been made to encourage; the use of environmentally friendly construction materials and innovative manufacturing processes, the application of construction products and related processes that reduces consumption of resources, embodied carbon and production of byproduct wastes, and the design of innovative products using recycled materials (European Commission, 2013). Research is therefore being extensively undertaken to explore through recycling, the potential of using wastes for the production of building materials in order to encourage natural resources conservation. Some findings are discussed in this review.

2.3.2.1 Environmental Impact of the construction Industry

The rapid population growth and the continuous growth of industrialization throughout the world together with increasing living standards, are gradually making the creation of the built environment to become a rising threat to the natural eco-system.

The construction industry activities are highly material intensive (Karade, 2010) and the continuous exploration of natural resources for the production of traditional materials including; clay, sand stone, gravel, cement, brick, block, tiles, paint, timber and steel utilized as building component in this sector constitutes a damaging effect on the environment. In Europe, the construction industry is responsible for the consumption of over 50% of all material extracted from the earth and generation of over 450 million tonnes/year of waste (European Commission, 2013). In the United Kingdom, the construction industry is regarded as the largest consumer of natural resources with over 400million tone of material consumed each year (WRAP, 2007). It is also estimated that this sector accounts for 10% of the total UK carbon emission (UNEP SBCI, 2009). Also at the global level, significant amount of natural resources consumption (Fig. 2.3) and pollution generation (Fig. 2.4) have been attributed to the construction industry. The global extraction of sand and gravel which are major mineral use in construction has been reported to represent 68% to 85% of about 59 billion tonnes of material mined from the earth every year (UNEP GEAS, 2014; Steinberger *et al.*, 2010; Krausmann *et al.*, 2009).

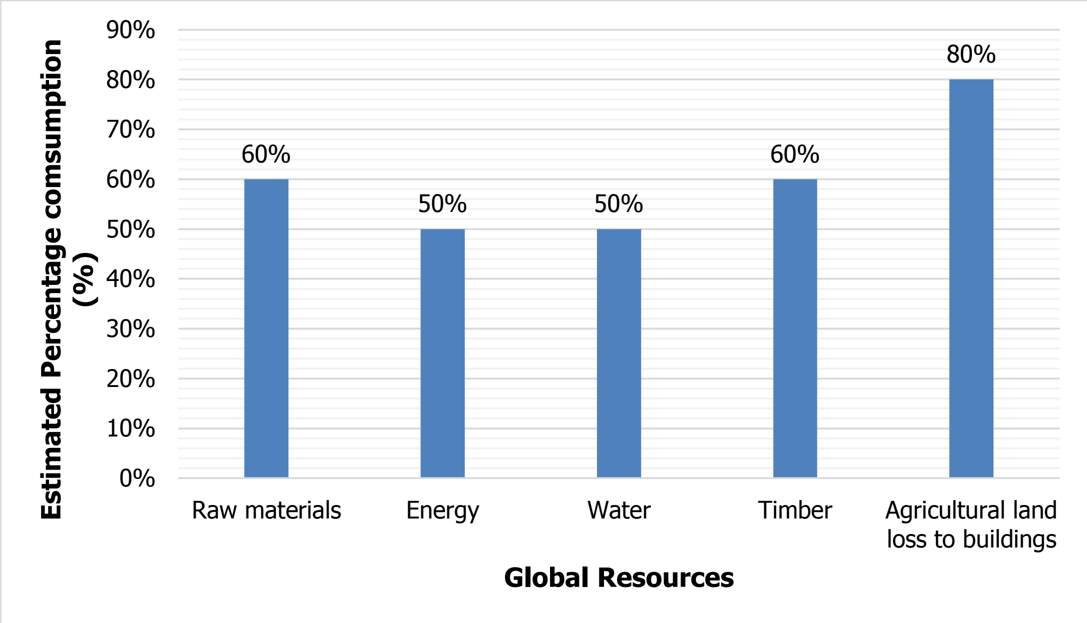


Fig. 2.3: Estimate of global resources consumption in building construction (Hawken et al., 1999)

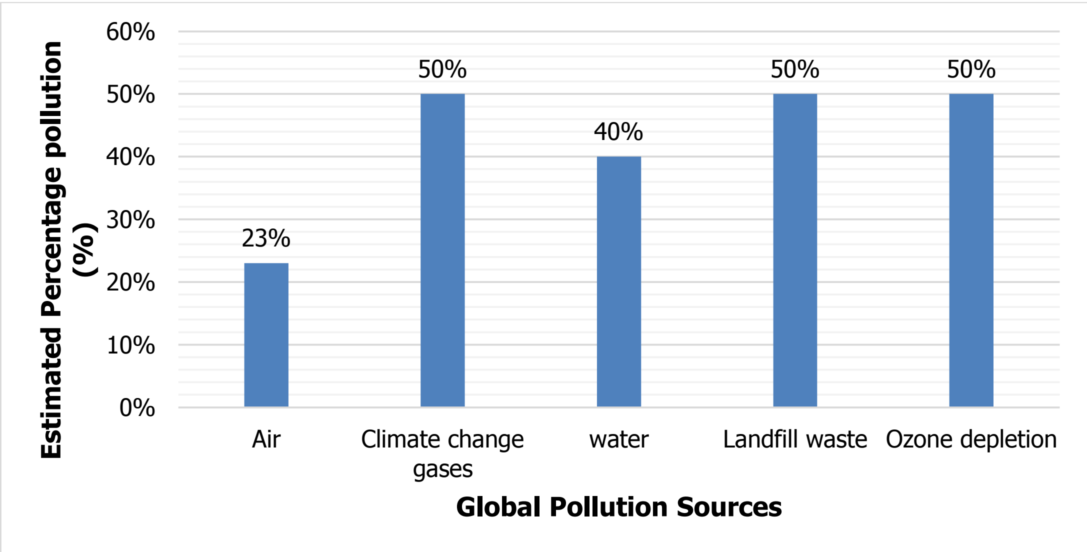


Fig. 2.4: Estimate of global pollution attributed to buildings (Brown and Bardi, 2001)

Other evidences of high natural resources consumption in the construction are highlighted in Chapter one of this thesis. Similarly, owing to the restriction of the manufacturing process and the raw materials of cement (which is a major building material in the construction industry), some fundamental disadvantages of Portland cement (PC) are still proofing difficult to overcome. About two major drawbacks with respect to sustainability were identified from literatures viz; enormous resources consumption and GHG emission. About 1.5 tonnes of raw materials is needed in the production of every tonne of Portland cement, at the same time, the amount of the carbon dioxide released into the environment during the manufacture of Ordinary Portland Cement (OPC) due to the calcination of limestone and combustion of fossil fuel is said to be in the order of one ton for every ton of OPC produced (McCaffrey, 2002). Apart from this, the extent of energy required to produce OPC is reported to be close to the amount expended for the production of steel and aluminium (McCaffrey, 2002). Therefore, the production of PC can be regarded as an extremely resource and energy intensive process. The overriding question that needs to be asked is; what are the implications of these impact on the environment?

2.3.2.2 Implication of Environmental Impact of the construction Industry

The continuous occurrence of the impacts mentioned above could lead to environmental degradation. Literatures have identified global warming, pollution, and natural resources depletion/collapse as the imminent danger of the impacts of the construction industry (WRAP, 2007; Sustainable aggregate, 2009; UNEP SBCI 2009; Giljum *et al.*, 2009). For example, UNEP SBCI (2009) reported that buildings are accountable for over 40% of global energy consumption and contribute an estimated one third of total global greenhouse gas emissions, largely through the use of fossil fuels during construction processes.

2.3.3 Inferences from the Literature Review on the Need for Recycling in Construction

Based on the findings from the reviews conducted to identify the need for recycling in construction, it is apparent that the implementation of recycling in construction industry represents a viable approach to address the two major global environmental concerns viz; unsustainable waste generation and the various notable environmental impacts of the building construction.

2.4 SUSTAINABILITY IN THE CONSTRUCTION INDUSTRY

Development is believed to be sustainable when it does not adversely affect the ability of the future generation in meeting their needs (World commission on environment, 1987). As awareness of the potential environmental impacts of building construction has grown, several efforts and suggestions are being made to avoid these adverse effects and to work towards impact mitigation measures. Some of this efforts and suggestions are discussed.

2.4.1 Efforts to achieve Sustainability in the Construction Industry

Substantial effort is being made in the United Kingdom to reduce the environmental impacts of materials used in construction. This is probably why the UK Government's strategy for Sustainable Construction features a section on materials, whose focus is to ensure responsible sourcing of construction products. This effort also includes the development of open and public databases for the embodied carbon of buildings, in order to provide access for stakeholder (such as: clients, planners, engineers, architects, building developers, quantity surveyors and other building professionals) in the construction industry to assess the eco-friendliness of their respective decisions and construction processes (Strategic forum for construction report, 2008). Few examples of UK government's efforts to offset the environmental impacts of its construction including; Life Cycle Assessment (LCA), Green Guide to Specification, Use of Recycled and Secondary product, Environmental Product Declarations (EPDs), Responsible Sourcing had been reported (UK Green Building Council, 2014).

2.4.2 Intellectual Suggestions to Achieve Sustainability in the Construction Industry

Mehta (2002) suggested the use of fewer natural resources, less energy and minimized carbon dioxide emissions in order to produce an environmentally friendly concrete. The Eco Innovative under the European Union commission, also encourages; the design of innovative products using recycled material, the use of environmentally-friendly construction materials and innovative manufacturing processes, the use of construction products and related processes that reduce consumption of resources, embodied carbon and production of by-product wastes (European Commission, 2013). (McCaffrey, 2002) suggested the use of lower amount of calcined materials in cement, reduced quantity of cement in concrete and decrease in the number of building using cement. Based on an investigation of the LCA of concrete and asphalt, Blankendaal *et al*., (2014) reported that the application of alternative cement types, in concrete is capable of reducing the environmental impact of concrete production by up to 39% (Blankeedaal *et a*l., 2014).

2.4.3 Inferences from Review of Sustainability in the Construction Industry

Based on the review of efforts and expert suggestions made towards achieving sustainability in the construction industry, it is apparent that implementations of eco-friendly construction processes (which encompasses reduced; consumption of resources, embodied carbon and production of by-product wastes) and eco-friendly construction materials (which encompasses; less/non-cement inclusion and recycled use of wastes) will go a long way to contribute to the much-awaited sustainability in the construction industry.

2.5 USE OF RECYCLED SOLID WASTES IN BUILDING MATERIALS

Large amount of solid wastes (including; plastic, metal, textile, wood, glass, paper and concrete) are being generated around the globe from various human activities, in both developed and developing countries due to population growth, rise in living standard and urbanization (Safiuddin, *et al*., 2010).

Extensive literature review (as summarized in Table 2.2) show that these wastes can indeed be utilized to produce different kinds of building materials (e.g. blended cement, aggregate, resin binder, concrete, blocks etc.) exhibiting desirable engineering properties. These findings indicated the suitability of this approach as an alternative disposal method for solid wastes to achieve environmental sustainability. The building construction industry is a major sector where a holistic utilization of these waste could be implemented, the reason being

Table 2.2: Summary of Recycled Use of Solid Waste in Building Materials

Solid waste	Recycling Technology	Recycled Use in building materials	References
Plastic	-Transesterification -Crushed into Aggregate -Grind to powder	Concrete/Mortar, resin binder (for polymer concrete). Fine aggregate, Thermoformable (wood plastic fibre) composite	Sam and Tam, 2002; Marzouk *et al.*,2007
Textile	Cut into Fibre	Lightweight concrete, Cement mortar elements, Insulation materials, reinforced concrete, Bricks	Briga-Sa *et al.*, 2013; Pereira-de-Oliveira *et al.*, 2012; Peixoto *et al.*, 2012; Binici *et al.*, 2012
Metal	-Melt -Reuse	Recycled steel, blended cement, Aggregate in high strength concrete and lightweight concrete, cementitious paste, bricks	Pappu *et al.*, 2007; Li and Sun, 2000; Shih *et al.*, 2004
Glass	-Reuse -Crushed into Aggregate -Grind to powder	Recycled window unit, cement replacement, filling material, recycled aggregate, tile, paving block, brick	Turgut and Yahlizade, 2009; Demir, 2009; Coventry *et al.*, 1999; Shao, *et al.*, 2000
Paper	Pulp (blended) Fibre (Shredded) Ash	Fibre reinforced cement composite, wall panel, building block, brick, thin cement sheet, low density board, composite panel, cement replacement.	Modry, 2001; Fuller *et al.*, 2006; Kinuthia et al, 2009; Ashori *et al.*, 2011.
Wood	-Reuse -Crushed into Aggregate -Combined with other materials	Plank, beam, door, floor boards, rafter etc. Lightweight aggregate Woodcrete (sawdust+ waste paper+ Lime) Wood chip concrete	Aigbomian and Fan ,2013; Masjuki *et al.*, 2008; Kasai *et al.*,1998.
Concrete	Crushed into Aggregate	Recycled aggregate, e.g. Coarse or Fine aggregate, Concrete bricks, Paving blocks	Tabsh and Abdelfatah, 2009; Poon, *et al.*, 2002; Levy and Helene, 2004; Khatib, 2005; Al-Mutairi and Haque, 2003.

its notable material intensive activities. Therefore, the possible utilization of solid waste in this sector stands to be a viable option for it disposal.

2.6 USE OF RECYCLED POST-CONSUMER WASTEPAPER IN CONSTRUCTION

Wastepaper can be described as used-up papers that are no longer useful for the purpose for which they were made or that have already served such purpose and are meant to be disposed off.

2.6.1 Availability of Wastepaper

Paper and paper products represent a considerable percentage of municipal solid waste stream in most developed and developing countries. At the global level, wastepaper represents the second largest component of the solid waste composition and futuristic estimates of global paper consumption indicated that high quantities of wastepaper will continue to be generated at developed and developing countries (Hoornweg and Bhada-Tata, 2012) (Resources Information Systems, Incorporated (RISI), 2007)). The reason for this may be attributed to the increasing demand for paper and paperboard that usually occur with rises in a country's GDP (Kinsella *et al.*, 2007).

Wastepaper has continued to form the largest components of the municipal solid waste stream in the United States and Europe for several years back. As far back as 1960 and up to 2013, percentage of paper and paperboard generation in the USA have evolved between over 30% and over 20% of the total solid wastes being generated (United States, Office of Resource Conservation and Recovery, 2015). In the UK, as at the year 2001, waste paper and paperboard represented; the second largest component of MSW accounting for 21% overall, the largest component of commercial waste accounting for 41.2% and the largest component of liter and street sweeping wastes accounting for 31% overall (Burnely *et al.*, 2007). Since 2005 up to 2013 period, the generation of paper and cardboard waste has continued to increase in Europe (Fig. 2.5). According to Eurostat data for the 28 European Union member states, paper and cardboard waste represents the largest packaging waste generated in Europe within the same period (Eurostat Statistics Explained, 2016).

At the global level, approximately 400 million tons of paper was being produced annually as at 2012 (FAO, Forest Product statistics, 2012) and the per-capital paper consumption is growing on a yearly basis and it is higher in developed economy than developing economy (Kinsella *et al.*, 2007). In 2004, the per-capital paper consumption in the USA was said to be approximately 317 kg/person/year, while that of China and Asia stood below 50 kg/person/year (see Fig. 2.6). A recent UNEP Global Waste Management Outlook (GWMO) article also reported the annual per capita paper consumption to be; 240 kg/capital/year for North America, 140 kg/capital/year for Europe, 40 kg/capital/year for Asia and 4 kg/capital/year for Africa (UNEP, 2015).

Therefore, considering the apparent increasing rate of per capital wastepaper consumption (as illustrated in Fig. 2.7) and the various predictions indicating a possible increase of global paper production from the present 450 million tons per year to 500 million tons by 2020 (Ali *et al.*, 2013) and the forecast of 60% increase in global demand for paper and paperboard from the 368 million tons recorded in 2005 to 579 million tons by the year 2021 (RISI 2007 in Kinsella *et al.*,2007), it is obvious that monopolizing the recycling of waste paper to paper production alone is not enough to solve the enormous quantity of waste paper generation.

An additional evidence of this is the amount of wastepaper that is still going into landfill and incineration, despite the high recycling rate achieved in few developed countries.

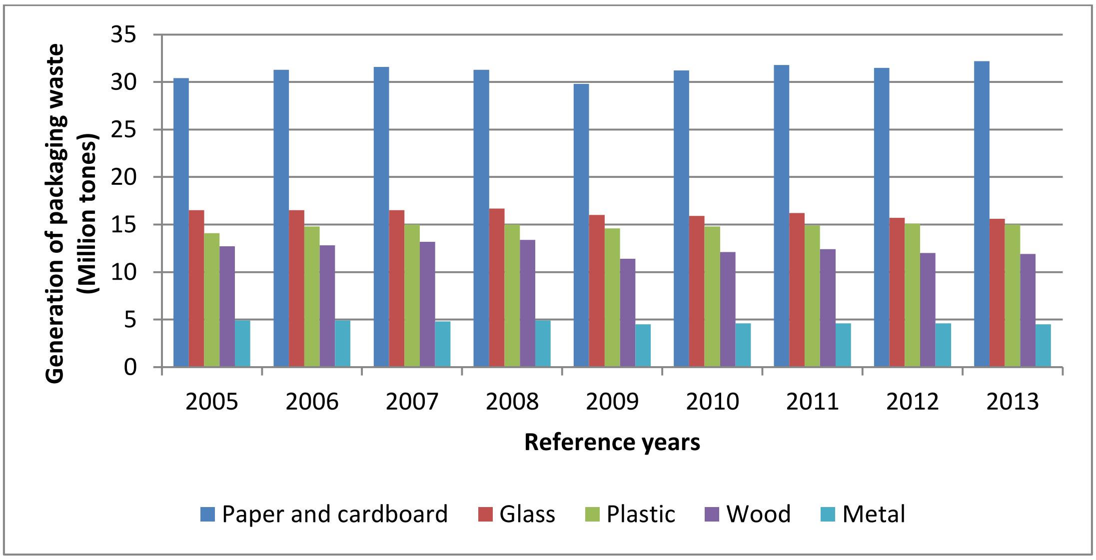


Fig.2.5: "Wastepaper" the largest component of packaging waste generated in Europe (2005-2013) (source: Eurostat statistics Explained, 2016)

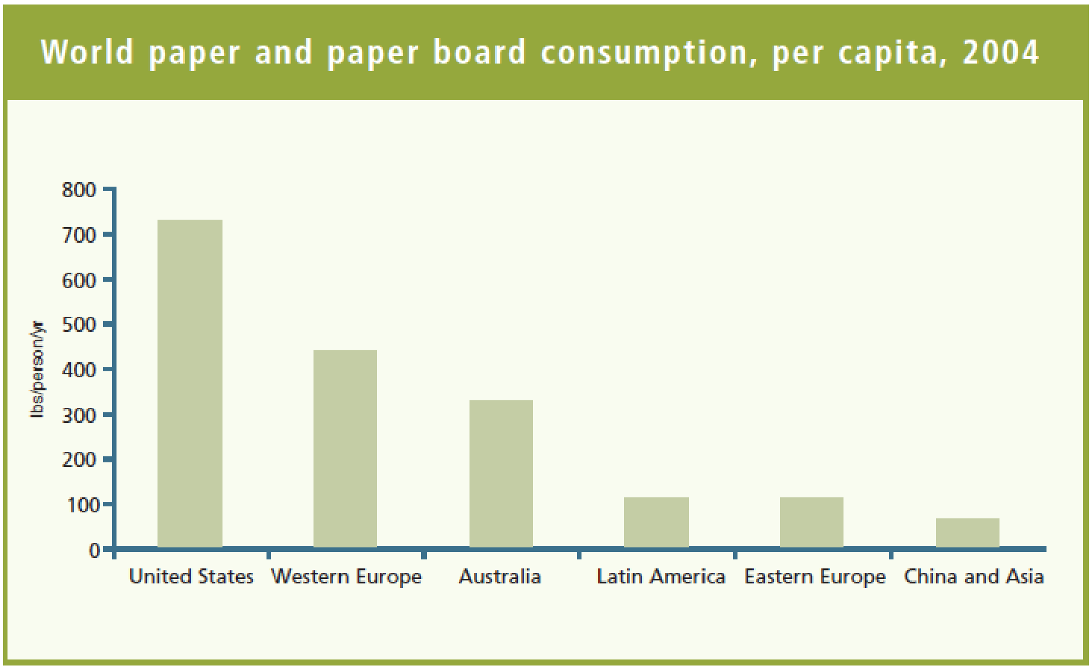


Fig. 2.6: 2004 Estimates of Global per Capital paper consumption (Source: Adapted from RISI (2005) in Kinsella *et al.*, (2007))

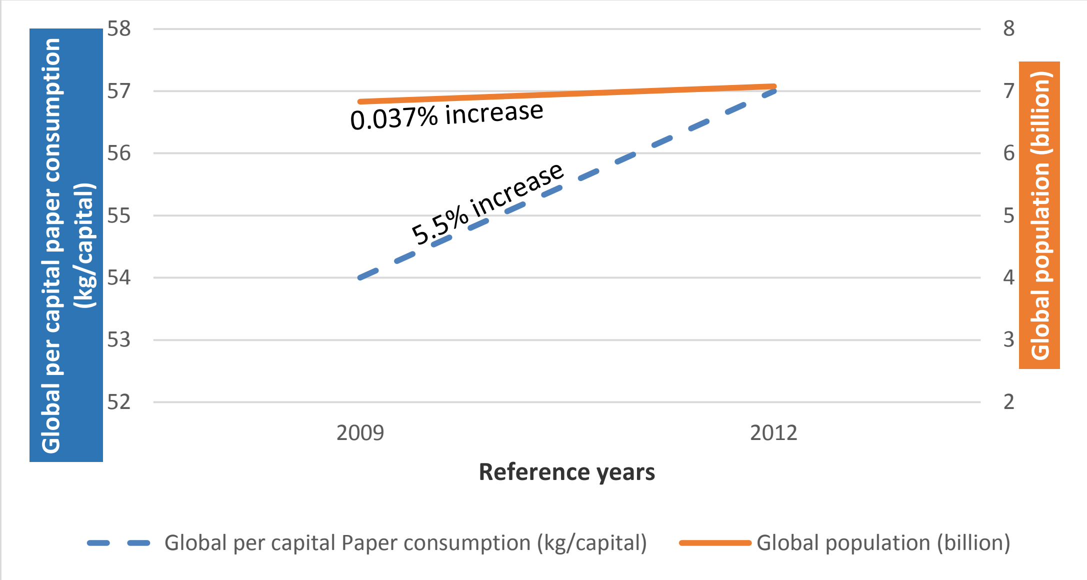


Fig. 2.7: Estimated Percentage Increase of Global per capital paper consumption, compared with percentage global population growth between 2009 and 2012 (Source: Estimated by the Author, using paper consumption and population information from; (The statistics portal, 2014) and (Hoornweg and Bhada-Tata, 2012) respectively.

For instance, an estimated volume of 10 million tonnes of paper and board which could have been recycled is still currently going into incineration and landfill in Europe, despite the 71.7% recycling rate achieved in 2012 (Confederation of European paper Industries (CEPI), 2014), 48 million tonnes is being disposed in USA (Nepal and Aghawal, 2014) despite the 65.8% recycling rate (Table 2.3). Also, contrary to the general believe that the advent of electronics will reduce the consumption of paper, literature evidence (Fig 2.7) shows that, there has been a continuous increase in the global consumption and utilization of paper and paper product at faster rate than that of the global population. This is indicated by the estimated 5.5% increase in global per-capital paper consumption at a corresponding 0.0037% increase in global population (Hoornweg and Bhada-Tata, 2012; The Statistics Portal, 2014).

Table 2.3: Wastepaper Percentage recycling rate and quantity disposed in landfill in some selected countries

Country	Percentage Recycling rate of Wastepaper	Reference Year	Wastepaper disposed into landfill	References
USA	65%	2012	48 million tons	Nepal and Aggarwal,2014
South Africa	57%	2011	728 743 tones	Department of Environmental Affairs (2012).
Europe	71.7%	2012	10 million tones	CEPI, 2014
	67.5%	2010	22 million tones	CEPI, 2009

Previous, forecast of paper production, consumption, and utilization in Europe also indicated an up to date continuous increase between 1995 and 2015 (Fig. 2.8). Fifteen years forecast of global paper consumption by grade (Fig. 2.9) (RISI, 2007) also suggests a continuous increase in consumption of different types of paper in the future which is an indication of continuous availability of wastepaper for recycling purposes.

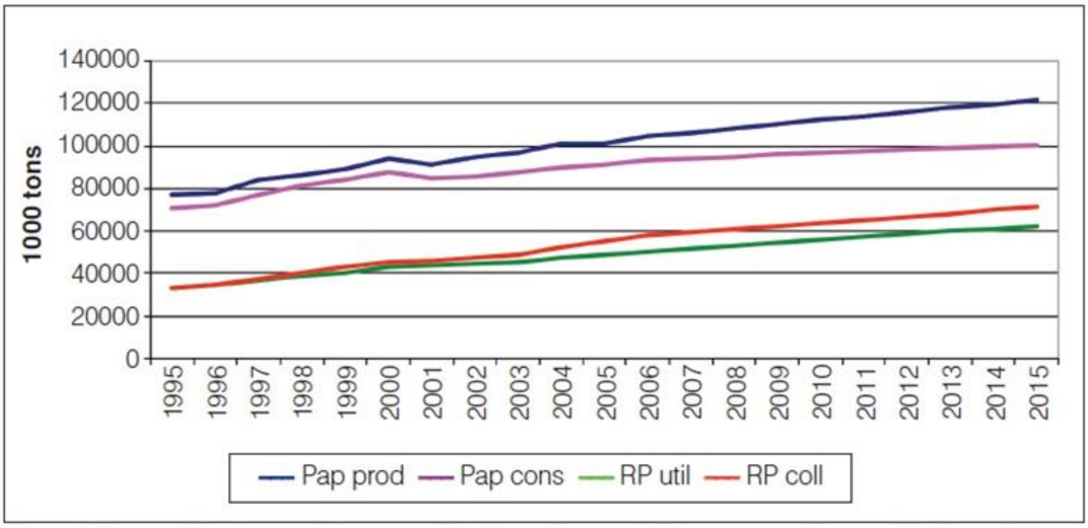


Fig. 2.8: 20 years forecast of development of paper production and consumption, recovered paper utilisation and collection in the European 1995 to 2015 (Source: Adapted from COST Action E48, 2010)

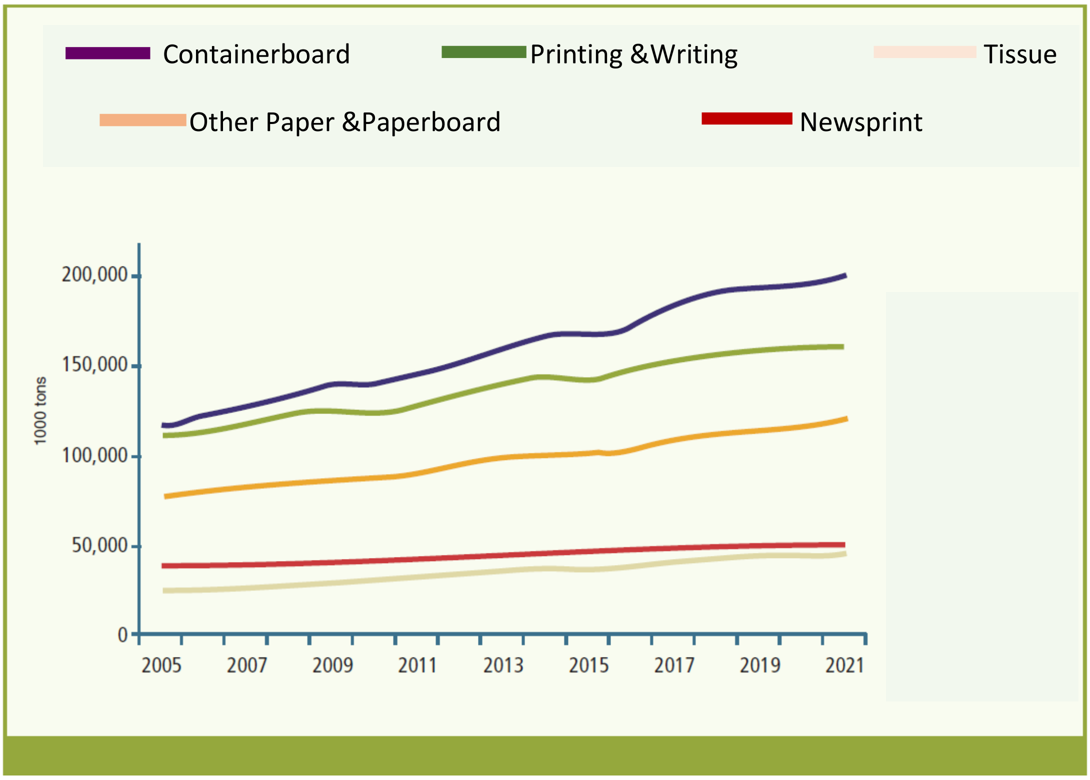


Fig. 2.9: 15 years forecast of World paper and paperboard consumption by grade, 2005–2021 (Source: Adapted from RISI (2007) cited in Kinsella *et al.*, (2007)).

2.6.2 Potential Impacts of Inadequate Disposal of Wastepaper

The need to explore alternative means of recycling wastepaper for productive use is paramount, considering the problems associated with its recycling back to paper products and the environmental impacts that could result from its inadequate disposal. Based on literature evidence, the problems which includes; the removal of contaminants, fibre shortening and high sludge production is commonly encountered during the recycling of wastepaper back into paper (COST E48 (2010); Albertson and Pope, 1999). Similarly, organic materials including wastepaper, decomposes slowly in landfill and releases methane which is a potent greenhouse gas (Levis and Barlaz, 2011). Aside from the reported challenges relating to scarcity of suitable land space for landfilling being experienced in highly urbanized areas such as the north-eastern US and most part of Europe, municipal landfills are said to be responsible for 34% of human-related methane emissions to the atmosphere, with major contribution resulting from decomposition of landfilled wastepaper (US EPA, 2007; US Composting council, 2011). The disposal of biodegradable waste into landfill is also prohibited in some countries (Barlaz, 2006). Presently, as part of the waste target review, the paper industry is proposing a wide ban on landfilling/ incineration of recyclable paper in Europe by the year 2020 (CEPI, 2014).

Therefore, to achieve an effective solution to the peculiar problem of wastepaper disposal along with the associated environmental concerns, the need to economize resources through the recycled use of wastepaper in construction and other engineering fields stand as a viable option for its disposal. This may also indirectly offset some of the notable environmental impacts of the construction industry such as high natural resources consumption, high energy usage, and greenhouse gas emission.

2.6.3 Previous Use of Wastepaper in Building Materials and the Associated Drawbacks

Based on literature evidence, there is potential for utilization of wastepaper to produce different kinds of building materials (Table 2.4). Wastepaper-based Building materials including; concrete, infill materials, plastering mortar, green cement have been reported to exhibit some behavior and properties that are desirable for application in construction (Nepal and Aggarwal, 2014; Zavala, 2013; Yun *et al*., 2007; Fuller *et al*.,2006; Decard *et al.*; 2001;). Thus, the use of wastepaper in making civil engineering construction materials and other engineering products can be considered as a sustainable way of addressing the ever increasing worldwide wastepaper availability, provided that the less adequate properties are improved upon.

For example, the possibility of producing suitable concrete binder from the combination of wastepaper sludge ash (WSA) and other wastes has been confirmed in the literatures. Research evidence has shown that an eco-friendly binder designated as "Green cement" produced from combination of WSA and granulated blast furnace slag (GGBS) enable the production of concrete blocks with better appearance, strength and durability, compared to those produced from the conventional Portland Cement (Nidzam and Kinuthia *et al*., 2010). Concrete produced from WSA-GGBS green cement have been confirmed to exhibit desirable properties, Kinuthia *et al*., (2009) reported that the performance of WSA-GGBS binder in Colliery Shale concrete production was next to the performance of Portland cement.

Table 2.4: Properties of Concrete Containing Wastepaper

Paper Uses in Concrete	Paper content (%)	Compressive strength (MPa)	Thermal conductivity (W/m.k)	Fire resistance	References
Papercrete	Not reported	0.96-1.1	Not reported	Not reported	(Nepal and Aggarwal, 2014)
	Not reported	1.7	Not reported	Not reported	(Nepal and Aggarwal, 2014)
	Not reported	1.12-2.36	Not reported	Not reported	(Kokinos, 2011)
	5%	34.0	Not reported	Not reported	(Yun *et al.*, 2007)
	20%-40%	0.195-0.990	0.10	-	(Titzman, 2006)
Infill material	72%	5.56	0.85	2hrs	(Mohammed, 2009)
Additional material in concrete	5%-20%	14.7 - 4.0	Not reported	Not reported	(Decard *et al.*, 2001)
	15%	15.67	Not reported	Not reported	(Abdul Ghani and Shukeri, 2008)
Plastering Mortar	40%-38%	2.51-1.86	Not reported	Good	(Aciu *et al.*, 2014)
Green Cement	WSA+ GGBS	Performance comparable to ordinary portland cement			Kinuthia *et al.*, 2009 ; Nidzam and Kinuthia *et al.*, 2010

In comparison to their disposal in landfill, which eventually leads to release of methane into the ground, the primary advantages of using wastepaper especially in building materials are the low density, low cost, stiffness, high filling levels possible, energy conservation, desirable strength to weight ratio and high availability resulting from increasing paper and board consumption (Fig. 2.7) throughout the world.

The main drawback of using waste paper in concrete includes; the high moisture absorption of the paper fibers and composites produced, which sometimes leads to reduced mechanical properties. Many of the concrete mixes where higher strength was obtained utilized very low percentages of wastepaper content and those mixes made with higher wastepaper content displayed lower compressive strength. The reason for this could be connected to the hygroscopic nature of paper fibre, which makes it to absorb more moisture than the amount required for cement hydration, thereby reducing the strength properties. The low-density boards produce from wastepaper also suffers from lack of dimensional stability for exterior application.

However, despite the associated disadvantages, reviewed studies showed that the building materials made from wastepaper possess desirable properties for several lightweight applications like partition, sound absorption, thermal insulation and low-cost housing.

2.7 INFERENCES FROM SECTION ONE OF LITERATURE REVIEW

This section had presented four major categories of literature review to establish theoretical basis as well as justify the need for the recycled use of wastes including wastepaper in the production of building materials as well as the need for this research. The findings from featured reviews have been summarized in the subsections (2.3.3, 2.4.3, and 2.6.3). Having establish the theoretical basis for the research in this section (i.e. 2.2 to 2.7), the next section (i.e. 2.8 to 2.15) will present the review of literature on; fundamentals of conventional masonry blocks, properties of wastepaper-cement-based blocks, drawbacks of wastepaper-cement-based blocks, cumulative summary of literature reviews, identified research gaps and the need for this research.

2.8 LITERATURE REVIEW ON MASONRY BLOCKS

This section presents the review of conventional masonry blocks; it discusses the fundamentals of conventional masonry blocks and its manufacturing technology, the properties of blocks containing wastepaper and the associated drawbacks. It also gives a brief summary of the entire literature review (both section one and section two), identified gaps in research and the need for the present study.

2.9 CONVENTIONAL MASONRY BLOCKS

Masonry blocks are walling units produced from mixture of natural sand or crushed stone dust commingled with cement and water and compressed into different shapes and sizes. Masonry block units usually develops strength required for the designed application after sufficient setting, hydration and hardening must have taken place (Baiden and Tuuli, 2004)

A masonry block is a composition of usually 1:6 mix of cement and sharp sand with the barest minimum of water mixture, and (in some cases) addition of admixture. They are molded and subjected to curing naturally (Anosike and Oyebade, 2012). BS 6073 (2008) and BS 6073(1981) defines block as a masonry unit whose dimensions in terms of the length or width or height exceeds that of bricks when applied in its normal position. Due to durability and aesthetic characteristics, masonry unit have been employed for construction of structures right from the beginning of civilization (Drysdale and Hamid, 2005). In African countries such as Nigeria and Ghana, masonry block units (popularly referred to as sandcrete blocks) are widely used as walling units and over 90% of houses in Nigeria are being constructed of them (Baiden and Tuuli, 2004; Anosike and Oyebade 2012). In the hardened state, masonry block has a high compressive stress and this strength increases with density. The range of minimum strength specified by the relevant standards including; BS 6073, (1981), BS 6073 (2008), pr EN772-2(1992), Nigerian industrial standard (NIS) NIS 87(2007), Nigeria building code, (2006), Ghana building code, (1989), New Zealand code (1998) are presented in Chapter three Section 3.5.3.1 of this thesis.

2.10 TYPES OF MASONRY BLOCKS

Over the years, masonry units have been categorized based on different criteria. Some of such criteria include; forms, sizes & shapes, constituent materials, applications, weight and core types. BS 2028 (BSI 1975) (now withdrawn) classified blocks into three types based on specified properties and uses, without reference to materials or method of manufacture, it distinguishes between the specified types A, B, and C based on density (see Table 2.5)

Table 2.5: Types of Masonry block according to (BS 2028 (BSI 1975))

Type	Name	Density (kg/m^{3})	Usage
A	Dense aggregate blocks	Not less than 1500	
B	Lightweight aggregate blocks	Less than 1500, but not less than 625	Load bearing walls
C	Lightweight aggregate blocks	Less than 1500, but not less than 625	Non load bearing partitions.

The NIS specifies two types of blocks; type A (load bearing) and type B (non-load bearing) based on their forms and sizes. These blocks can also be solid or hollow. Approved sizes for masonry (sandcrete) blocks specified by NIS are presented in Table 2.6. Other types of masonry block available in Nigeria are decorative and ventilating blocks which are sandcrete blocks with no voids or webs and they are generally used for non-loadbearing wall construction. Hollow blocks specified by NIS exhibits voids with core area greater than 25% of the gross area, they are produced from lightweight aggregates and are applied for both loadbearing and non-loadbearing wall construction (Anosike and Oyebode, 2012). Also, the BS EN 1996-1:2005, grouped masonry units into different types based on configurations in terms of form and core types (see Table 2.7).

Table 2.6: Types of Masonry/Sandcrete Blocks According to NIS and Their Usage

Type	Work size (mm) Length x height x thickness	Web thickness	Usage
Solid blocks	450x225x100	N/A	For non-load bearing and partition walls
Hollow	450x225x113	25.00	For non-load bearing and partition walls
Hollow	450x225x150	37.50	load bearing wall
Hollow	450x225x225	50.00	load bearing wall

Source: NIS 587: 2007

Table 2.7: Categories of Masonry blocks according to BS EN 1996-1 :2005

Configurations	Grouping
Blocks containing less than 25% formed voids	Group 1
Blocks containing greater than 25% but less than 60% formed vertical voids	Group 2
Blocks containing greater than 25% but less than 70% formed vertical voids	Group 3
Blocks containing greater than 25% but less than <50% formed horizontal voids	Group 4

The BS 771 series which is a performance-based standard categorize masonry units based on constituent materials (Table 2.8) and the part 1-6 of the series addresses each type of masonry unit produced from a particular constituent material. For simplicity of selection and specification, aggregate concrete block details such as; block description, dimensions, tolerance category, and strength, have been recommended to categorize block units (see Table 2.9a) (Concrete block Association (CBA), 2007).

Table 2.8: Categories of Masonry Blocks According to the BS EN 771 Series

BS EN 771 Series	Mansonry Unit types
BS EN 771-1	Clay masonry units
BS EN 771-2	Calcium silicate masonry units
BS EN 771-3	Dense concrete masony units
BS EN 771-4	Autoclave aerated masonry units
BS EN 771-5	Manufactures stone masonry units
BS EN 771-6	Natural stone masonry units

Therefore, depending on the rationale for classification, masonry blocks can either be lightweight or normal weight, loadbearing or non-loadbearing, solid or hollow, cellular, aggregate, clay, concrete, natural stone, autoclave aerated, group 1, 2, 3, 4 etc.

2.11 PROPERTIES OF MASONRY BLOCKS

Masonry blocks are expected to exhibit specific properties, to make them suitable for use as wall elements. These properties are usually achieved through adherence to relevant standard recommendations on mix ratio, curing, and quality of constituent materials. Some of the properties that must be satisfied include; suitable compressive strength, low shrinkage, low moisture movement, low thermal movement, and denseness and durability (BS 6073, 2008; BS 6073, 1981).According to CBA data sheet 1 (2007), the properties of concrete blocks available in BS EN 771-3 are more detailed than those specified in BS 6073-1 but the use of the necessary ones are recommended for specification purposes because some of them are peculiar to certain countries (CBA data sheet 1, 2007), for instance, the flexural strength is said not to be applicable to block units in the UK. The requirements of the BS 771 series which masonry blocks are expected to satisfy depending on their intended applications includes: dimensions, configuration, density, thermal performance, durability, water absorption by capillarity, moisture movement, water vapour permeability, reaction to fire (spread of flame), shear bond strength and flexural bond strength. Table 2.9b shows few examples of the standard properties that non-loadbearing masonry blocks are expected to satisfy.

Table 2.9a: CBA recommended criteria for categorizing Aggregate concrete blocks

Aggregate concrete Block details (recommended for categorization)	Meaning/ examples	Reference code
Block description	Range of block types being available from by CBA manufacturers in the UK e.g. standard common blocks with 440 mm x 215 mm face size, Close textured/Paint grade common blocks, standard facing blocks, etc.	
Dimensions,	Standard block dimensions specified in terms of length x width x height	
Tolerance category	Length width and height deviation Tolerance categories D1 and D2 as specified	BS EN 771-3
Strength,	Compressive strengths of Aggregate concrete blocks ranging from 2.9 N/mm^2 to 40 N/mm^2 (Solid) and 2.9N/mm^2 to 22.5 N/mm^2 (cellular and hollow).	
	2.8 N/mm2	BS EN 6073-1, 2008; BS EN 6073,1981
Net dry density	Net dry density aggregate concrete blocks in the range of 650 – 2400 kg/m^3	
Configurations	In terms of void types and size	BS EN 1996, 2005

Table 2.9b: Standard properties of Non-loadbearing Masonry Blocks

Properties	Requirements	References
Compressive strength	1.5 MPa	BS EN 771-4:2011
	For other Standard requirements, applicable in selected countries	See Chapter 3 (Section 3.8.3.1)
Bulk Density	300-1000 kg/m^3	BS EN771-4:2011
	625-1500 kg/m^3	BS EN 2028: 1975
Water Absorption capacity	240 kg/m^3	BS EN 2028:1975 (now withdrawn)
Dimensional Check	For standard permissible deviation in length, width, and Heights.	See Chapter 3 (Section 3.8.3.4)

2.12 CONVENTIONAL MASONRY BLOCK MANUFACTURING TECHNOLOGY

Masonry blocks are manufactured from a carefully orchestrated step by step process, the adequacy of which usually has impact on the quality of blocks produced. Research evidence has shown that the property of masonry blocks can be influenced by processing parameters including; quality of constituent materials, batching of aggregates, mixing of constituent materials, method of molding/production, curing, transportation, storage, mix ratio, and water content (Barden and Tuuli, 2004). Therefore, it is important to understand the fundamentals of each of the processes in order to produce an acceptable block. The knowledge of these processes may also be used as a basis for the production of alternative blocks from different constituent materials.

2.12.1 Size and Forms of Masonry Block

Masonry blocks are available in different sizes and forms. The sizes and shapes of masonry blocks are mostly produced to a standard size to facilitate building construction. The length, width, or height of a block is usually greater than that specified for a brick. As a standard, the height of the block does not exceed either its length or six times its thickness (Gage, 1971; Kreh, 2014). The length and width of the block are mostly kept constant while the thickness varies from 75 mm to 225 mm for depending on the application (Baiden and Tuuli, 2004), in African countries, thickness of 100 mm are mostly used for partition walls while 150 mm are generally used for external and load-bearing walls. Generally, blocks could be produced as solid or hollow, as defined by BS 6073 (BSI 1981). Solid blocks are void-less but can have end grooves to improve handling and bonding. Hollow blocks have a much more obvious cavity right through the block. The total volume of the cavity is usually recommended to be limited to 50% of the total volume of the block (Tovey, 1981; Hendry and Khalaf, 2001).

2.12.2 Constituent Materials of Masonry Blocks

The quality of masonry blocks depends on the quality of the fine aggregates, sand, cement, and water employed for their production.

2.12.2.1 Aggregate

Aggregates are granular materials obtained from natural or artificial sources and are employed as mineral filler materials in the constituents of both masonry and concrete (EN 13055-1:2002; BS 882:1992). Materials like sand, gravel, crushed rock and other mineral fillers are used as aggregates.

The two main types of fine aggregates mostly used for the production of conventional masonry blocks are; natural sand and crushed stones. Recently, many innovative blocks have been developed from manufactured aggregates and waste materials have been used as partial or full replacement of sand in masonry blocks. Some of the artificial aggregates and waste materials previously explored for masonry block production include: cement kiln dust (Abdel-Raheem *et al*., 2003), crushed waste glass (Al-Jabri *et al*., 2009), rice husk ash (Oyekan, 2007), polystyrene foam (Herki and Khatib, 2013), vermiculite, (Oyekan and Kamiyo ,2011), vermiculite and polystyrene beads (Oyetola and Abdullahi, 2006).

The conventional fine aggregates (sand) for masonry blocks should comply with BS 882 (BSI 1996) and those regarded as lightweight fine aggregates are expected to comply with BS 3797; 1990. The sand should be clean and devoid of organic or deleterious matters. Tests such as sieve analysis, a silt/clay content test, and an organic content test are usually conducted on aggregate samples to ascertain their suitability for masonry block production (Gage 1971), additional tests including; loose bulk density and loss on ignition are required for lightweight aggregates.

2.12.2.2 Cement

Cement is a powdery material with adhesive and cohesive properties capable of bonding mineral fragments (e.g. granular sand) into a compact whole (Neville, 2011). It is also known as hydraulic binder due to its capability to set and harden by chemical reaction in the presence of water.

According to the Ghana Standards Board (1995), Portland cement that conforms to BS 12:1991 is suitable for sandcrete block production. Cement produced under controlled factory conditions, and the resulting product accompanied by a Quality Assurance (QA) certificate is regarded as a guarantee that the quality of the cement is of acceptable quality (Anosike and Oyebade, 2012). The quality of cement can however be affected by the storage conditions prior to use, it is therefore recommended to be stored in a well-ventilated sheds at least 150 mm above the ground (Neville, 1995).

2.12.3 Manufacturing of Masonry Block

The processes involved in the manufacturing of masonry block includes; the batching of aggregates, followed by the mixing of constituent materials (taking full cognizance of the mix ratios as specified by the relevant standards e.g. BS 2028: 1975 recommendations for mix ratios and limits for water cement ratios), then the molding and curing of the masonry block, followed by the proper storage and transportation to the location for utilization.

2.13 USE OF WASTE MATERIALS IN MASONRY BLOCK PRODUCTION

In many countries around the world, the price of most conventional building materials is increasing and in some countries there is a general paucity of natural materials that are suitable for construction. The need to promote and achieve environmental sustainable construction is paramount, considering the prediction of 70% global growth of construction market by 2025 (GCPOE forecasts, 2013) and the notable environmental impacts of building construction. In recent years, there has been an increase in the consumption of raw materials in the construction industry at a rate far exceeding their replacement (UNEP, 2014).

These factors explain the reasons for the various concentrated research effort towards the development of alternative building materials suitable for use as a partial or full replacement of either cement or aggregates, which are considered the main ingredients used in the manufacturing of blocks. Therefore, it is apparent that, the use of recycled waste and by-product materials in the manufacturing of masonry blocks could provide a viable solution to the problem. This can yield the dual benefits of reducing the costs of disposal and minimizing environmental pollution problems that arise from the manufacturing of such materials. The use of waste materials in the manufacturing of concrete blocks has been the subject of an intensive research work in recent years. The prediction that "what we build, what we build with and how we build it will soon be transformed by a number of environmental considerations" (HM Government Industry Strategy, 2013) is already becoming a reality, as various studies to develop alternative building materials from municipal solid wastes such as paper, wood glass, metal textile etc. have been conducted with desirable conclusions.

2.14 PROPERTIES OF WASTEPAPER CEMENT BASED BLOCKS: REVIEW OF PAPERCRETE BLOCKS

The ever-present need for low-cost housing, the booming interest in construction materials that are created with minimal harm to the environment and the sustainable design trend being embraced by developers, architects, and engineers have prompt researchers to seek for alternative building material from a least expected source; "WASTE PAPER". The emphasis is to achieve an ecological sensitive recycling of the large amount of wastepaper still ending up in landfill, incineration and open dumps (in developing countries).

Researchers are therefore exploring through experimentation, all ways by which wastepaper can be recycled into an environmental friendly building material with focus on sustainability, this has therefore led to the production of a building material known as papercrete. Papercrete is one of the most popular cement-based-wastepaper blocks, it is produced from a combination of recycled paper, Portland cement, sand and other optional materials, such as fly ash, and Styrofoam, glass etc. According to Fuller *et al.*, (2006), it can be used in many ways as blocks, panels, poured in place, augured, pumped, sprayed, hurled, trowelled on and used like igloo blocks to make a self-standing dome or applied over a framework to make a roof or dome. The details of the properties reported for different mixes of papercrete blocks have been well documented in the literature (Akinwumi *et al.*,2014; Nepal and Aggarwal, 2014; Fuller *et al.*, 2006; Modry, 2001) and are summarised in Table 2.10. The benefits such as; reduced landfill use and provision of affordable housing for millions of people (Solberg Gordon, 2000), good sound absorption (Fuller *et al.*, 2006), good insulation, and lightweight that papercrete blocks have to offer, as lead to experimentation to obtained data that details some of its structural properties.

2.15 INFERENCES FROM THE REVIEW OF PROPERTIES OF PAPERCRETE BLOCKS

Based on extensive literature review, the properties reported for papercrete suggested the suitability of its use as block unit for wall construction (Akinwumi *et al.*, 2014; Tizman, 2006; Fuller *et al.*, 2006; Modry, 2001). Its properties as reported by different research findings are summarized in Table 2.10. Aside from the reported compressive strength of papercrete blocks, Fuller *et al.* (2006) further observed and emphasized the importance of its stiffness in determining its properties. This is evident in that it exhibits ductile failure, rather than brittle failure displayed by concrete and some papercrete building were reported to have been standing after 20 years with no signs of deterioration (Fuller *et al.*, 2006).The parameters including mix ratio, use of admixture and curing procedures were reported to influence its properties, the similarities of these parameters to those that affect the properties of conventional masonry blocks may be due to the presence of cement in the constituents of papercrete.

However, certain drawbacks, which include; inconsistency in the compressive strength reported for papercrete blocks, the lack of a standard mix composition for different application, the high-water absorption and the lowering of compressive strength associated with increase in wastepaper fibre are worthy of note. For example, there seems to be no account of elaborate experimental report to back up some of the findings reported by its notable practitioners, [e.g. 0.96-1.1 MPa reported by Barry Fuller and the 1.7 MPa reported by Kelly Hart (Nepal and Aggarwal, 2014)]. Also, the available findings with experimental back up are made from different constituents and mixes. It also lacks standardization by the international building code.

Table 2.10: Properties of cement-based wastepaper blocks (As collated from previous research papers).

Cement based wastepaper blocks	Paper content	Compressive strength (MPa)	Thermal conductivity (W/m.k)	Density kg/m3	Coefficient of capillary water absorption	Water Absorption	References
Papercrete	Not reported	0.96-1.1	Not reported	Not reported	Not reported	Not reported	Nepal and Aggarwal, 2014
Papercrete	Not reported	1.7	Not reported	Not reported	Not reported	Not reported	Nepal and Aggarwal, 2014
Papercrete	Not reported	1.12-2.36	Not reported	Not reported	Not reported	Not reported	Kokinos, 2011
Papercrete	20% - 40%	0.195-0.990	0.10	Not reported	Not reported	Not reported	Titzman, 2006
Hollow block	40%	1.84	0.35	Not reported	4.48	25.65%	Modry, 2001
Hollow block	35.7%	1.4	Not reported	1060.74	Not reported	41%	Akinwumi *et al.*, 2014
Block	25%	1.64	Not reported	Not reported	Not reported	Not reported	Chandarana *et al.*, 2014

Note: Tensile Strength was found to be 0.052-0.195 MPa (Titzman, 2006)

There is also the need to assess the influence of method of production (e.g. use of presses) on its properties especially for its application as building block.

Considering the environmental impacts associated with the production of cement, the use of Portland cement as part of papercrete's major constituents is believed to be offsetting its environmental friendliness; for example, the percentage of cement utilized in most of the mixes reviewed exceeds the percentage of wastepaper content. Also, the comparison of the percentage of cement content incorporated in the papercrete mixes with respect to its total dry constituent material reveals that papercrete blocks are being made from higher percentage of cement compare to the amount of cement present in the 1:6 nominal mix composition for conventional masonry blocks (Table 2.11).

Table 2.11: Comparison of Estimated Percentage cement content in papercrete mix compositions with that of Conventional Masonry blocks.

Mixes reference	**Type of block**	**Reported Mix Composition (from literature review)**	**Estimated Percentage Cement content (by weight of dry constituent) (%)**
Fuller (2014)	Papercrete	(27 kilograms of paper) + (43 kilograms of Portland cement) + (29 kilograms of sand)	43%
Curry T. (as cited in Fuller, 2014)	Papercrete	(25% reground Styrofoam) + with (three sacks of Portland cement) + (to be added to 75 pounds of hammer-milled waste paper) indicating: (40.75 kg of Styrofoam) + (129kg of Portland Cement) + (34.0194 kg of wastepaper)	63%
Akinwumi *et al.*, 2014	Papercrete	35.7% cement, 35.7% sand and 28.6% Wastepaper (i.e. 1 : 1 : 0.8 paper : cement : sand mix ratio)	35.7%
Chandarana *et al.*, 2014	Papercrete	25% paper, 25% sand and 50% cement (i.e. 1:1:2 paper: cement : sand mix ratio)	50%
BS 2028: 1975; Baiden and Tuuli, 2004	Conventional Masonry block	one-part cement to six part of aggregate (1:6 mix ratio) indicating: 14% cement and 86% aggregate.	14%

2.16 SUMMARY OF LITERATURE REVIEW AND IDENTIFIED RESEARCH GAPS AND THE NEED FOR THE PRESENT STUDY

Based on the review of literatures conducted on the state of the art in this thesis, it is apparent that several building materials have been produced from waste materials and particularly wastepaper. The major reason being to address the high consumption of natural resources associated with the building industry for the purpose of sustainable development in the built environment.

This extensive literature review showed that most building materials containing wastepaper along with innovative blocks produced from waste paper suffers three identifiable major drawbacks including:

- High water absorption
- Excessive thickness swelling in the presence of water
- Low strength with increasing wastepaper fibre content

The high water absorption characteristic as well as excessive thickness swelling associated with different building materials containing wastepaper fibres (e.g. concrete, fibre cement boards, particle boards etc) reported by several research findings (Akinwumi *et al*., 2014; Acui *et al*., 2014; Ashori *et al*., 2011; Yun *et al.,* 2007; Tizmany, 2006) were attributed to the apparent hygrospcopic properties of wastepaper fibre. Also, further findings from the literature review indicated that cement -based wastepaper blocks (e.g. papercrete block) exhibit low strength with increasing paper fibre content (Akinwumi *et al*., 2014; Zavala, 2013; Yun *et al*., 2007; Decard *et al*., 2001) despite the considerable amount of cement utilized as binding medium and the effort of previous research to improve this property by increasing cement content has proven abortive (Brock, 2011).

Considering the sensitivity of cement hydration to water/binder ratio (Shamshai *et al*., 2012; Xincheng, 2012; Neville, 2011) and the apparent hygroscopic properties of wastepaper fibre, the drawback of strength reduction being observed in wastepaper–cement-based blocks (e.g. papercrete) may be attributed to the contradiction that exists between the hygroscopic properties of paper fibre and the moderate water requirement for cement hydration. This indicates that, the high water/cement ratio resulting from increasing wastepaper content lowers the strength of the building material concerned. Also, the approach of utilizing considerable quantity of cement as means of strength improvement by previous research efforts has been considered detrimental and believed to be offsetting the environmental friendliness of the concerned wastepaper-based blocks (e.g. papercrete). A typical evidence of this undermined eco-friendliness is the fact that many of the cement-based-wastepaper blocks contain higher percentage of cement in their constituents compared to the percentage of cement present in the nominal mix composition for conventional masonry blocks.

Based on the outcome of the literature review, there is presently no recorded evidence of research undertaken to investigate the possibility of utilizing hundred percent non-hydraulic/non-chemical-based binder (e.g. waste additive from biological source) for the production of wastepaper-based blocks.

Therefore, to effectively address these research gaps, there is need to investigate the possibilities of developing building materials from wastepaper without the use of hydraulic cement as binder. Thus, this ongoing research aims to develop an environmentally friendly, lightweight, non-loadbearing block from wastepaper with the use of waste additive (from biological source) as binder instead of the conventional hydraulic binder. The proposed block is expected to serve as:

- A sustainable alternative to the conventional block commonly produced from majorly natural aggregates and traditional hydraulic binders (e.g. OPC).

- A more sustainable alternative to the wastepaper-cement-based blocks in terms of strength properties and constituent materials.

Also, the proposed application of the block for non-load bearing application is expected to protect it from exposure to the weather element thereby indirectly addressing the water absorption characteristic.

Borrowing from the principle of agglomeration and biomass densification in which; biomass/lignocellulosic materials (whose composition are similar to that of wastepaper fibre) in combination with natural binder/waste additive are densified to produce durable briquettes and pellets with desirable characteristics at low molding/extrusion pressure (Kaliyan and Morey, 2009a; Pietsch, 2008; Pietsch, 2002). It is apparent that the lignocellulosic characteristics of wastepaper fibre can enable its combination with natural binder/waste additive from biological source to produce a more ecofriendly wastepaper-based lightweight block. Therefore, this study proposes the use of waste lactose (a byproduct of dairy industry) as binder for the production of the Cement-less Wastepaper-based Lightweight Block (CWLB) being proposed in this research.

The environmental benefits that accrue with the successful development of this block includes: natural resources conservation, practice of industrial ecology, waste recycling, reduction in environmental pollution, reduction in greenhouse gas emission, reduction in energy consumption etc.

The remaining chapters of this thesis present the details of the experimentation conducted to develop the proposed Cement-less Wastepaper-based Lightweight Block (CWLB).

CHAPTER THREE: RESEARCH METHODOLOGY

3.1 INTRODUCTION

This chapter presents the details of the methodology and the experimental program that was followed for the production and testing of the cement-less wastepaper-based lightweight block (CWLB) that is being developed in this research.

3.2 RESEARCH EXPERIMENTAL PROGRAMME

Published literature have very little or no information on the manufacturing of recycled wastepaper-based lightweight block with the use of waste lactose as binder. Majority of published articles on wastepaper use in building materials centres on the use of wastepaper in conjunction with cement as binder to produce building materials such as Papercrete (Fuller *et al*., 2006a, 2006b; Santamaria *et al*., 2007). Papercrete is a building material produced from a combination of recycled paper, Portland cement, sand and other optional materials, such as fly ash, and Styrofoam, glass etc. The presence of recycled paper in the constituents of papercrete and its usual application as block in building construction (Fuller *et al*., 2006a) makes it to be of close relevance to the CWLB under study. However, the mix proportions for CWLB differ from those of papercrete, in that the latter incorporates hydraulic binder (cement) as its binding medium. Also, its strength development is based on the cement hydration and its mixes contain high range of water/binder ratio. Furthermore, it forms paste in the fresh state due to the inclusion of hydraulic cement in its constituents and high water/binder ratio. On the other hand, the CWLB (being developed in this research study) exhibits fibrous form in the fresh state as it was made from majorly cellulosic material and inert/unreactive binder and without cement as binder. It rather incorporates the use of a waste additive obtained as a byproduct of dairy industry as binder. The research gaps being addressed by the development of CWLB are expatiated in Chapter 2 (Section 2.16) of this thesis.

Due to lack of explicit information, this study utilized majorly the experiences that were gained from the preliminary laboratory experimentation coupled with the limited relevant/applicable knowledge from making of papercrete (as described in the literature review) to develop the mix proportioning process for the CWLB.

Owing to the fact that the CWLB under study is new, written engineering standards do not exist for its production and testing; the standards used to ascertain its quality were selected based on intended application rather than constituent materials and method of production. It should be noted that, the Eurocode 6 which is a performance-based code that addresses the design of masonry structures permits the declaration of performance-based specification for newly invented walling products as a basis for assessing their suitability for the intended application (BS EN 1996-1:2005; Egenti *et al.*, 2014). This indicates the ratification for designing masonry unit and or its alternative product to satisfy the properties needed for its intended application regardless of its constituent materials.

Therefore, considering the proposed/intended/designed application of CWLB for non-load bearing purposes in wall construction, the BS EN 771-4:2011 was selected as the major reference standard for ascertaining the quality of the CWLB mainly because it appeared to be the most relevant. As evidence BS EN 771-4:2011 is a European Standard that specifies the characteristics and performance requirements (e.g. strength, density, dimensional accuracy etc.) of autoclaved aerated concrete (AAC) masonry units intended for use as load bearing and non-load bearing applications in every part of walling including single leaf, cavity, partitions, retaining, basement and general use below ground level, including walling for fire protection, thermal insulation, sound insulation and the fabric of chimneys (BS EN 771-4:2011). It is worthy of note for this study that the reference is to the intended application and not to the material or method of production. Other related standards which includes; BS EN 772-1:2011, BS EN 772-13:2000, BS EN 772-16:2011, BS 5328-2:1997 BS EN 6073:1981, BS EN 6073:2008, and BS 2028:1975 were used as guidelines for the relevant parts of the experimentation and to ascertain the quality of CWLB for the intended application.

In order to develop the cement-less wastepaper-based lightweight block (CWLB) technology, a rigorous trial and error process was used. The focus was to, develop an efficient mix proportioning process for the block prior to the commencement of the main experimentations scheduled to address the second, third and fourth objective of the research (including: identification and studying of the salient parameters that influences the mixture proportioning of CWLB, the determination of the optimum mix composition for the block and determination of CWLB's engineering properties).

As far as possible, the current practice used in the manufacture and testing of masonry block presently in use for building construction was followed in order to ease the promotion/acceptability of this new material to the building construction industry upon its successful development. To simplify the development process, the compressive strength was selected as the major benchmark parameter for selection of efficient mixture composition. This is because of the intrinsic importance of the compressive strength in the structural design of masonry structures (Neville, 2011). Also, BS EN 5328-2:1997, section 2.1, recommends strength testing as an important part of assessing the conformity of a designed concrete mix to specification. An overview of the experimental program is presented in Fig. 3.1.

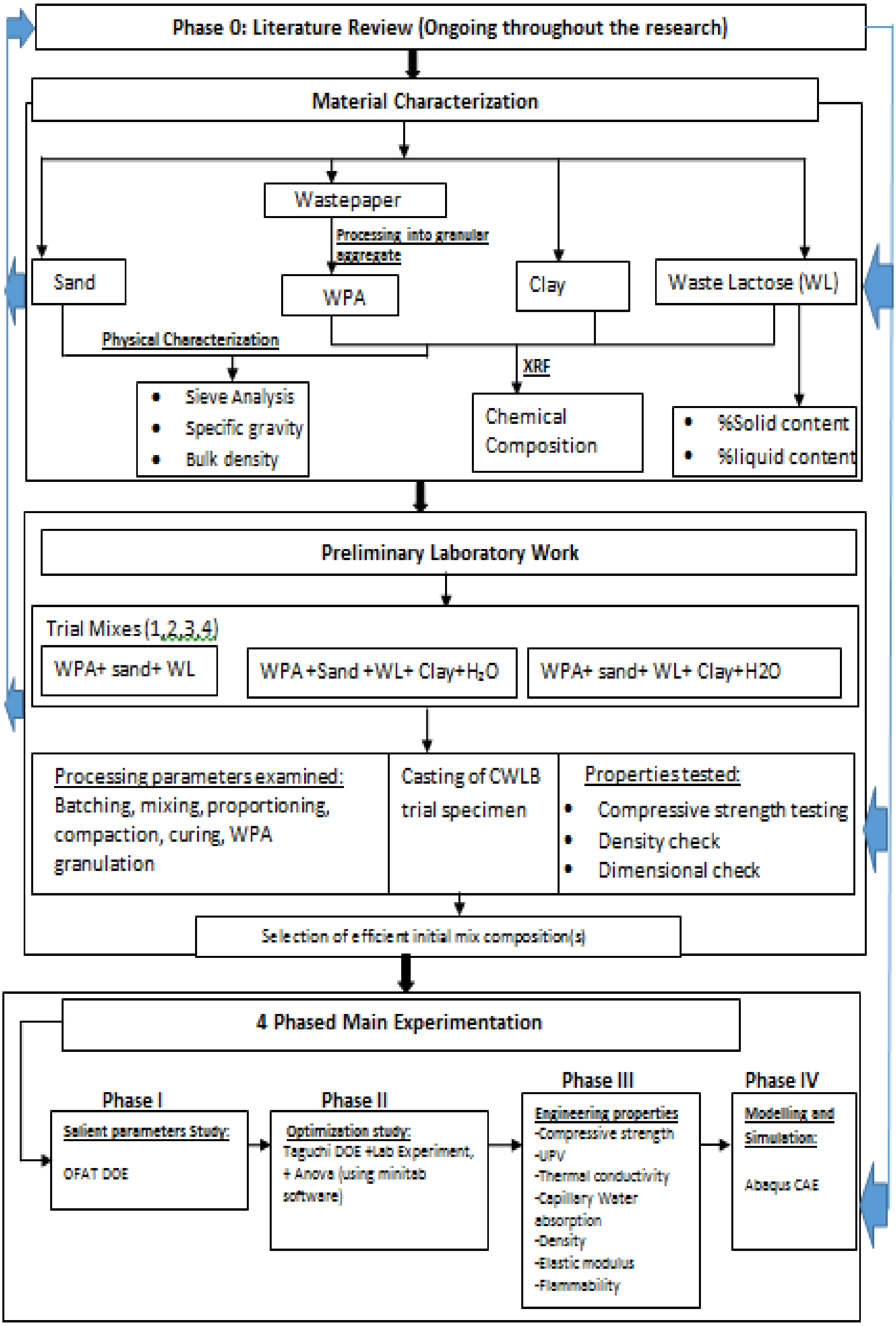


Fig. 3.1: Overview of Research Experimental Program

3.3 SCOPE OF THE STUDY

This study utilized wastepaper (old newsprint), and small amount of fine aggregate (sand) as filler material and waste lactose (a waste by product of the dairy industry) as binder (see Table 3.1), instead of the combination of fine aggregate, water and OPC presently being used in masonry production.

Similar to the case of masonry block in which aggregate usually occupy about 75% of the total constituents (Neville, 2011), the CWLB was designed in such a way that the filler materials (wastepaper) occupied larger percentage of the total mass of the block as much as possible. Also, in order to minimize the effect of the properties of the constituent materials on the properties of the CWLB, each of the materials for this study were obtained from a single source and in a single batch each.

Table 3.1: Uses of constituent materials in CWLB

Materials	Uses in constituent of CWLB
Wastepaper	Aggregate Filler
Sand	Aggregate Filler
Waste additive (Waste lactose)	Binder
Stoneware Clay	Natural admixture

3.4 MATERIALS

The materials used in this study include, wastepaper, sand, waste additive (waste lactose), stoneware clay and water. In keeping with the responsible sourcing approach suggested by the UK government for sustainable construction, the materials utilized for the development of the CWLB were selected with focus on environmental sustainability. Wastepaper was selected to serve as filler material for the CWLB due to; its increasing availability at various parts of the world (Kinsella *et al.*, 2007), its lightweight and stiffness properties (Levlin, 1999; Fuller *et al.*, 2006). The binder used was obtained as an industrial byproduct in line with the practice of industrial ecology suggested by Mehta (2002). Small quantities of sand was used as fine aggregate to add weight to the block in alignment with the suggestion of McCaffrey (2002) regarding the use of fewer natural resources for building material production.

3.4.1 Waste Paper

In this experimental work, post-consumer wastepaper (i.e. old newsprint) (Fig 3.2) which was obtained from a newspaper publishing company in Wolverhampton city, West Midlands, United Kingdom was used as a major aggregate filler material.

Fig 3.2: Post-Consumer Wastepaper (old newsprint)

3.4.1.1 Processing of waste paper into usable form

The processing of the wastepaper into a usable form prior to its application in the laboratory experimentation for the manufacturing of CWLB was considered important, due to the fact that they were obtained in the form of sheets. Therefore, the old newsprints were systematically processed into an artificial lightweight aggregate designated as wastepaper aggregate (WPA). The detail of the processes involved in the production of WPA (types; A, B and C) is elaborated in sections 3.4.1.2 and 3.4.1.3. The approach of processing wastepaper into dried granular form was employed because it reduces the amount of water required for mixing (Zavala, 2013) and gives room for application of the resulting WPA in a conventional manner (Brock, 2011)

3.4.1.2 Processing of Wastepaper to Wastepaper Aggregate (WPA)

In order to process the wastepaper to wastepaper aggregate, a decision was first made on the form in which the wastepaper was to be applied. Based on literature reports on papercrete production processes, wastepaper has been applied in sheet form and in shredded form by different papercrete practitioners. However, using wastepaper in these forms have been accompanied by the need to use a considerable amount of water for mixing with other constituent materials.

Given the fact that the CWLB under study was designed to be made from different constituent materials with peculiar characteristics, it was considered paramount to ensure that the wastepaper form adopted should be such that it can be easily handled, stored and mixed with other constituent materials with a minimal quantity of water. Therefore, the use of the wastepaper in granular form was considered and adopted.

Hence, one of the initial steps taken at the onset of preliminary experimentation for CWLB is the processing of wastepaper into wastepaper aggregate (WPA). This facilitated the easy processing of CWLB. This approach is different from the method commonly being utilized by papercrete practitioners (e.g. Fuller, 2014; Santamaria *et al.*, 2007; Solberg, 2001 etc.) for the preparation of wastepaper use in production of wet papercrete, but it is almost similar to the concept/approach used by Brock, (2011) for the production of ''dry application papercrete" in his US patent.

Wastepaper used for the production of wet application papercrete is usually comminuted along with other constituent materials in a very big mixer with considerable amount of water. This usually results in a highly watery fresh papercrete mix (similar to slurry) which when manually molded into block requires about two to three months to dry and be ready for use (Fuller *et al.*, 2006b) and when molded using hydraulic press usually drains out excess mixing water during molding (Papercrete block press, 2013). On the other hand, the approach utilized by Brock (2011) for the production of dry application papercrete involved the drying of wet pulp prepared from mixture of newsprint, sand and water to a moisture content below that which could have initiated hydration with cement. Then followed by subsequent addition of extra sand and Portland cement, according to the inventor, this approach enabled the dry mix to be handled, stored and applied in a normal manner.

However, in this study, only the wastepaper was processed into a granular aggregate which can be handled, stored and applied in a conventional manner. This method was considered more practicable both for the simplification of mixture proportioning process of CWLB and for its field production in the future as it enables the WPA to be produced in one batch and to be ready for use at any time. Brock (2011) had previously used a similar approach to produce a dry granular papercrete mix which are usually stored conventionally prior to application in concrete production or precast blocks.

3.4.1.3 Procedure for Making WPA

As schematically presented in Fig. 3.3**,** the wastepaper was shredded with the use of a strip shredder. The shredded wastepaper was soaked in a moderate quantity of water for 4 days. The soaked shredded wastepaper was comminuted in a mortar mixer for approximately 20 minutes. The resulting smaller grained wastepaper fibres were drained to get rid of excess water and was sieved using a 6.3 mm aperture BS sieve size to obtain regular particle sizes/granulation. The resulting wet WPA was subjected to drying in an oven at a temperature of 75 ^{o}C for 4 days. The resulting in artificial lightweight wastepaper aggregate (WPA) which exhibits a particle gradation ranging from 4 mm to 0.125 mm (see Fig. 3.4).

Fig 3.3: Schematic of Procedure for making WPA

Fig 3.4: Shredded Wastepaper and Resulting WPA

3.4.1.4 Types of WPA Explored

Three types of the WPA (type A, B, and C) were explored during the preliminary experimentation. Each of the WPA types A, B and C in ascending alphabetical order were produced as an improvement over the previous type (in terms of their particle sizes and processing method) and they were utilized at different stages of the experimentation as required. The details of the extended processing method for WPA-type B and WPA-type C have been shown in Fig. 3.3 and details of the application of each of the WPA types in the process of development of CWLB is shown in Table 3.2.

Table 3.2: Details of different types of WPA explored and their Application in CWLB

WPA Type/Designation	Description	Particle size range	Processing method	Application
WPA-type A	Coarse	4mm-0.125mm	Systematic (See Figure 3.3 section 3.4.1.3)	Trial mixes 1, 2 and 3 (i.e. TM1, TM2, and TM3)
WPA -type B	Fine	1mm-0.063mm	Milling of WPA-type A using a planetary ball milling machine at a rotation speed of 360rpm for 15minutes	Trial mix 4 (i.e. TM4)
WPA -type C	Medium	passing BS sieve 3.35 mm	Screening/sieving of WPA-Type A using 3.35 mm BS sieve.	Main experimentation

3.4.2 Waste Additive (i.e. Waste Lactose (WL))

For the purpose of this study, waste lactose (Fig. 3.5) which is a waste byproduct of dairy processing industry was obtained from dairy industry in Wolverhampton, United Kingdom, and it was used as binder for the production of the CWLB. Chemical analysis was carried out on the waste lactose to determine its chemical composition.

Waste lactose (WL) was chosen as binder because of its availability and due to the fact that, it is a waste byproduct of the dairy industry whose inappropriate disposal could result in serious environmental problem. According to (Audic *et al.*, 2003) world cheese production generates more than 145 million tonnes liquid whey per year, out of which 6 million tonnes is lactose. A recent literature estimated world whey production to be around 180 to 190 million out of which approximately 50% is being treated for use in feed and pharmaceutical industry (Baldasso *et al.*, 2011), which means that the remaining 50% is being disposed off. Due to its high BOD which is reported to range between 34-45 mg/liter of whey (Mawson, 1988), the need to dispose lactose in an environmental friendly manner as been advocated by researchers and dairy industry Practioners (Audic *et al.*, 2003). In terms of management, the disposal of whey (a major source of lactose) poses both economic and environmental impacts (Mollea *et al.*, 2013), due to its high biological oxygen demand (which is largely attributed to the lactose content) (Kellam and Wansbrough, (anonymous)). This characteristic makes the disposal of whey/lactose to be a threat (causing oxygen depletion) to soil nutrient when disposed on the ground surface and a similar threat to aquatic life when disposed in the water body (Kellam and Wansbrough, (anonymous)). It's potential for use as binder in processes other than excipient purpose, was first reported by Fehiti in 1979. This author; Fehiti *et al.*, (1979) confirmed the suitability of lactose as binder through a study of its application as a binding medium in the extrusion of steel shavings to produce aggregate suitable for use in construction (Fehiti *et al.*,1979). The same source reported its previous use in brick and concrete production in North America. However there is no record of any research attempt to explore this further since then. Also, lactose has previously being identified as a good concrete setting retarder suitable for use in high temperate environment (e.g countries like Parkistan) (Khan and Baradan, 2002).

Fig 3.5: Waste Additive (i.e. Waste Lactose) Used as Binder for CWLB

3.4.3 Sand

The fine aggregates (sand) (Fig. 3.6) currently in use by the local concrete industry in Wolverhampton United Kingdom was obtained from its relevant suppliers and used as an additional aggregate filler material for the production of the CWLB. It was ensured that the fine aggregate (sand) meet the relevant British Standard (BS 882) (BSI 1996) by conducting tests to examine the particle size distribution (sieve analysis), specific gravity and loose bulk density as recommended by the standards.

Fig 3.6: Sand Utilized as Additional Aggregate

3.4.4 Admixture

In this study, stoneware clay (Fig. 3.7) was utilized as an admixture in the constituent of CWLB. The organic nature of the constituent materials of CWLB necessitated the incorporation of relevant admixture to correct the possibility of mould growth which is commonly associated with organic materials (e.g. cellulosic building materials) (Parrott, 2009; Andrews, 2002). Based on the outcome of the first trial experimentation during the preliminary study, 5% stoneware clay (measured by weight of WPA) was incorporated as a natural admixture to offset the susceptibility of CWLB to mould growth when subjected to mould prone conditions.

Evidence from the literatures has shown that building materials containing organic materials like paper/cellulose, wood, paper, paper-faced drywall or carbon-based material, carpeting, or batt insulation have the tendency to exhibit mould growth (Parrott, 2009; Andrews, 2002; Masonry Canada, 2004; Ontario

Association of Architects, (2003); PUB08-1192DN17 Designers notebook, 2008) because their organic components may act as food source for such growth. However, further research evidence showed that most fungi/mould cannot thrive at pH value range of 5 to 8 (i.e. neutral to slightly acidic). For example materials including; lime washes and concrete were said to have been capable of resisting fungal growth due to their high pH value range of (10 to 13) (Masonry Canada, 2004; Ontario Association of Architects, (2003; PUB08-1192DN17 Designers notebook, 2008). A similar occurrence was observed on the first set of CWLB trial specimen produced from trial mixtures in which the waste additive served as both the binder and mixing water. Tiny bit of cleanable mould growth [which may have resulted from a number of factors including; curing temperature, humidity of curing environment, organic content of the specimen, alkalinity, spore and moisture (Ontario Association of Architects, 2003)] appeared on the surface of the specimen after 28 days of curing at ambient condition (20 ^{0}C temperature) and at 20% relative humidity. Thus, considering the reported resistance of material with high alkalinity (including; fired clay, bricks, lime washes, cement, concrete) to mould growth (Masonry Canada, 2004; Ontario Association of Architects, 2003; PUB08-1192DN17 Designers notebook, 2008), 5% stoneware clay (measured by weight of wastepaper content) was incorporated as a natural admixture to raise the alkalinity of CWLB mixture beyond the level at which mould could thrive.

Fig 3.7: Stoneware Clay utilized as Admixture

3.5 CHARACTERIZATION OF CONSTITUENT MATERIALS OF CWLB AND THE PROCEDURES EMPLOYED

The constituent materials of CWLB which includes: WPA obtained from wastepaper, the sand used as additional aggregate filler, stoneware clay used as admixture and WL used as binder were characterized to determine their parametric properties which include: particle size distribution (sieve analysis), loosed bulk density, and specific gravity. In addition to this, the WL was further examined to determine its percentage solid and liquid content.

The sieve analysis, loose bulk density and the specific gravity were determined in accordance with BS 812-103:1985, BS 1097-3:1998, and ASTMC 128 (2015) respectively. The fine aggregates (sand) utilized for masonry blocks production are usually expected to comply with BS 882:1996. The sand should be clean and free from all deleterious matter. Therefore, BS 882 recommends tests such as sieve analysis, a silt/clay content test, and an organic content test to be performed on samples to ascertain the suitability of the sand before using it for masonry blocks. However, for the purpose of manufacturing CWLB, tests which include sieve analysis, bulk density, and specific gravity test were considered necessary to determine its physical properties, while the silt/clay content test and the organic content test were exempted due to the fact that the CWLB being developed contains majorly organic materials and does not contain cement. The procedures adopted for the sieve analysis, specific gravity and loose bulk density tests are respectively presented in the Sections 3.5.1.1, 3.5.2.1 and 3.5.3.1 of this Chapter.

Analytical test was also conducted on the WPA, WL and the clay to determine their chemical compositions. Two different analytical methods were employed to investigate the chemical composition of the constituents of CWLB. The inductively coupled plasma (ICP) method was used to analyse the waste additive and the X-Ray Fluorescence (XRF) was applied to determine the chemical composition of the WPA and the Clay utilized as admixture. The essence was to identify the elements present in these materials for the purpose of evaluating their expected behavior in the mixture proportioning and processing of CWLB. The procedures adopted for the ICP and XRF test are presented in the Sections 3.5.4 and 3.5.5 of this Chapter.

3.5.1 Sieve Analysis

This test was performed to determine the percentage of different grain sizes contained within the fine aggregate (sand). The essence was to determine the distribution of the particles, in accordance with to the BS 812-103:1985 recommendation.

Sieve analysis of aggregate is significant in the sense that, the distribution of different grain sizes affects the engineering properties of soil. Grain size analysis provides the grain size distribution, and it is required in classifying the soil or aggregate samples. Aside this, in masonry block production technology, sand is applied as a filler and a key indicator of the expected compressive strength of masonry blocks as it's usually occupies about 75% of the volume of the mix. According to literatures, sand with large percentages of finer grains requires more cement and water to coat their particles thereby leading to excessive water to cement, a phenomenon which usually leads to the production of weaker and more porous masonry blocks (Baiden and Asante, 2004). It was therefore paramount to determine granulation property for each of the dry constituents of CWLB in order to identify their grading and the implication of same for the proportioning and processing of CWLB.

3.5.1.1 Sieve Analysis Procedure

About 500 g representative oven dried sample having largest particles of the size of 4.75 mm was weighed. The soil sample was broken into individual particles using a mortar and a rubber-tipped pestle. (The idea was to break up the soil into individual particles, not to break the particles themselves.). The mass of the sample was determined accurately to 0.1 g (W). A stack of sieves was prepared in such a way that, sieves with larger openings were placed above sieves with smaller openings with the sieve at the bottom being 0.063 mm. A bottom pan was placed under sieve 0.063 mm. The measured soil sample was poured into the stack of sieves from the top. The cover was placed on the top of the stack of sieves. The stack of sieves was run through a sieve shaker for about 10 to 15 minutes. The sieve shaker was stopped and the stack of sieves was remove from the shaker, weight of each sieve with its retained soil was carefully weighed and recorded. In addition, the bottom pan with its retained fine soil was weighed and recorded .

The equipment and materials used for the test includes: a set of standard sieves, mortar and pestle, balance sensitive to 0.1 g, thoroughly oven-dried (or air-dried) soil/material sample and a timing device

3.5.2 Specific Gravity

The absolute specific gravity is the ratio of the mass of the oven dried sample to the mass of an equivalent volume of distilled water taken at a particular temperature (mostly 23±2 ^{0}C) (Neville, 2011). It is usually referred to as apparent specific gravity in situation where capillary pores are believed to be absent in the volume of the solid sample. Therefore, the apparent specific gravity was determined for the sand and clay used in this study and the term absolute specific gravity was considered to be appropriate for the specific gravity determined for the WPA, due to its fibrous and porous characteristics. The specific gravity for each sample of materials tested was determined in accordance with ASTM128 (2015).

3.5.2.1 Procedure for specific gravity

A 500 cm^3 density bottle was partially filled with water at 23 ^{o}C temperature. A 500 g of the oven dried sample of the material being tested was introduced, followed by the addition of water up to 90% of the density bottle capacity. The bottle was agitated to eliminate air bubbles and the temperature of the bottle and its content were adjusted to 23 ^{o}C by partial immersion in water. The bottle was towel dried. Having taken the following measurements:

- The mass of oven dried sample (A) was measured in air
- The mass of the density bottle with water to the calibration mark (B)
- The mass of density bottle with specimen and water (C)

during the experimentations, the apparent (absolute) specific gravity was calculated using equation (Eqn. 3.1)

$$Apparent\ specific\ gravity = \frac{A}{B+A-C} \qquad \text{-----------------Eqn. 3.1}$$

3.5.3 Loosed Bulk Density

The bulk density of a material is a measure of how densely packed the material is and it usually depends on the shape and particle size distribution of the material.

Based on BS 812-2:1995 the bulk density of aggregate can be determined either in the loosed state or in the compacted state. The loosed bulk density of the materials used in this study was determined in accordance with the method specified in BS 1097-3:1998. The loosed bulk density of the materials used in this study was determined in accordance with the method specified in BS 1097-3:1998.

3.5.3.1 Procedure for loose bulk density

The test was carried out on two samples. The aggregate sample was dried to a constant mass on an oven at 105 ^{o}C. The container placed on a horizontal surface was filled to overflowing by discharging the aggregate from a height of 25 mm above the top of the container. After filling, the surface of the aggregate was strike levelled with aid of a trowel. The mass of the aggregate in the container was determined to the nearest 0.01 kg and the loosed bulk density for each sample was calculated in kg/l using equation (Eqn. 3.2)

$$Loose\ bulk\ density = \frac{Mass\ of\ Aggregate\ (Kg)}{Volume\ of\ container(litre)} \quad \text{----------------------------Eqn. 3.2}$$

3.5.4 Inductively Coupled Plasma (ICP) and Its Procedure

The chemical composition of the waste additive sample (i.e. the waste lactose utilized as binder) was determined using the inductively coupled plasma atomic emission spectrometry (ICP-AES) method carried out with the aid of SPECTRO CIROSCCD Nr. ICP-32 (Fig. 3.8).

In order to meet up with the requirement of the ICP spectrometer regarding the purity of material feed, the waste lactose was subjected to filtration (using filter paper) in order to separate the solid and liquid component. The liquid component was feed directly into the ICP Spectrometer while the solid was digested before being feed into the ICP spectrometer.

The inductively coupled plasma (ICP) spectrometer is an instrument commonly employed for identification of trace elements in solution. It operation involves the injection of liquid samples into an argon gas plasma surrounded by a strong magnetic field. Also, it principle involves the excitement of elements in the sample by the argon gas plasma, followed by the emission of energy from the electrons at a characteristic wavelength as they come back to ground state.

Fig. 3.8: SPECTRO CIROSCCD Nr. ICP-32 (Source: Hamood, 2013)

The emitted light is then measured by the optical spectrometry. In the literature, this method which is alternatively referred to as inductively coupled optical emission spectrometry (ICP-OES), is reckon to be an efficient procedure for identification and quantification of elements in a sample (Hamood, 2013; Labcompare, 2013).

3.5.5 X-Ray fluorescence (XRF) and Its Procedure

The chemical composition of dry constituents of CWLB including the WPA sample and the Clay sample was determine using the X-Ray fluorescence (XRF) spectrometer (SPECTRO XEPOS XRF system) (Fig. 3.9). The X-Ray Fluorescence (XRF) spectrometer is an x-ray instrument commonly utilized to identify chemical elements in solid, liquid and powdered samples (Hamood, 2013). This method which is capable of measuring from as low as sub ppm up to 100% (sector 2013) depends on interactions between electron beams and x-rays with samples. The complicated principle of operation of the XRF spectrometer involves the release of some tightly held electron through energy radiation which leads to instability of atoms and the subsequent replacement of some missing inner electrons with outer electrons.

Fig. 3.9: SPECTRO XEPOS XRF system (Source: Hamood, 2013).

After a couple of other process that takes place within the system, the elements present in the tested samples are identified by the fluorescent X-rays (Geochemical Instrumentation and Analysis, 2013).

3.6 SIEVE ANALYSIS, SPECIFIC GRAVITY, LOOSE BULK DENSITY AND ELEMENTAL COMPOSITION OF CWLB'S CONSTITUENT MATERIALS

Table 3.3 and Figure 3.10 shows the grading of the dry constituents of CWLB. The granulation displayed by WPA ranged from 4mm to 0.063mm. As a standard limit, aggregates exhibiting particle sizes not larger than 4mm are usually categorised as fine aggregate (Neville, 2011). Each type of WPA tested can be categorised as fine artificial aggregate because the grading of their particle sizes compares well with the grading limit for fine aggregate.

Table 3.3: Sieve Analysis of Dry Constituent Materials

Sieve sizes (mm)	WPA Type A	WPA Type B	WPA Type C	Sand	Natural admixture (Clay)
	% Passing	% Passing	% Passing	% Passing	% Passing
8	100	100	100	100	100
4	96.2	100	100	99.4	100
2	54.5	94.4	57.5	97.5	100
1	10.0	23.1	10.6	95.1	99.87
0.5	0.7	3.0	5.1	91.4	77.61
0.250	0.6	0.8	1.5	36.9	44.21
0.125	0.4	0.3	0.7	6.8	4.34
0.063	0.0	0.0	0.0	0.5	0.47
pan	0.0	0.0	0.0	0.0	0.0

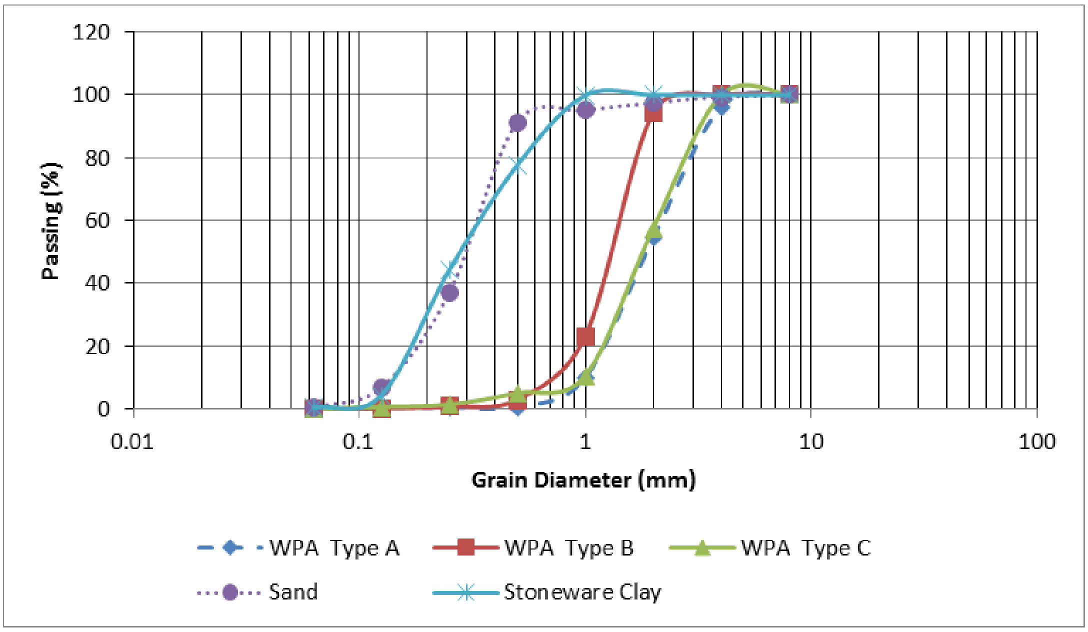


Fig. 3.10: Sieve analysis of dry Constituent of CWLB

The grading displayed by the sand and the clay samples were also satisfactory for the production of the proposed block.

Table 3.4 shows the specific gravity, loose bulk density, % solid and % liquid content for the constituent materials of CWLB. Natural aggregate usually exhibits specific gravity range between 2.6 and 2.7 but the values of specific gravity for artificial aggregate usually fall considerably below or above the range for natural aggregate (Neville, 2011). The specific gravity for each of the WPA-types A, B and C were measured as 0.661, 0.631 and 0.118. The loose bulk density of WPA types A, B and C obtained based on BS 1097-3:1998 were measured as 0.120, 0.103 and 0.120 respectively. These result comes in line with the literature evidence regarding the properties of artificial aggregates as the specific gravity values for WPA were considerably below the 2.63 value obtained for the sand sample tested and the loose bulk density values for WPA were considerably below the 1.428

obtained for the tested sand sample. Aggregates exhibiting loose bulk density not more than 1200 kg/m^3 (1.2kg/l) are said to be light in weight (BS 3797:1990). These findings indicate the lightweight properties and the voluminous characteristics exhibited by WPA.

Table 3.5 shows the chemical characteristics of the CWLB constituents including the; Waste additive (utilized as binder), clay (utilized as admixture) and WPA (utilized as aggregate filler). The result shows that each of the materials tested contains the major chemical components of cementitious materials in small proportion, indicating their inert characteristics

Table 3.4: Other Physical Properties of Constituent Materials

Properties	Material					
	WPA type A	WPA type B	WPA type C	sand	Waste additive	Natural admixture (Clay)
Specific gravity	0.661	0.631	0.650	2.63	1.04	0.895
Loose Bulk density(kg/l)	0.120	0.103	0.12	1.428	N/A	0.9112
Percentage solid (%)	100	100	100	100	23	100
Percentage Liquid (%)	0	0	0	0	77	0

Table 3.5: Chemical Characteristic of Waste Additive

Elements	Waste additive		Natural admixture (Clay)	WPA
	Solid part	Liquid part		
	ppm	ppm	% composition	% composition
Al	0.03	0.01	21.360	13.133
Ca	5.42	6.09	0.643	49.495
Fe	0.08	0.02	6.052	1.923
K	6.60	28.87	2.986	0.284
Mg	0.40	3.06	0.996	7.320
S	0.78	2.15	0.0806	3.268
Si	65.71	27.20	67.879	24.577

3.7 PRELIMINARY LABORATORY WORK

The preliminary laboratory work was conducted to develop a suitable mixture proportioning process for the manufacturing of CWLB being a new material. The main objectives were:

- To familiarize with the making of CWLB
- To understand the effect of sequence of adding the proposed binder (i.e. waste lactose) to the solid constituents in the mixtures
- To observe the behavior of the mixture and determine if the use of admixtures will be required.
- To observe, understand and study the behavior of the fresh CWLB mixtures and the compatibility of the constituent materials.
- To develop the process of mixing and curing regime

- To understand and select a set of efficient trial mixes from the numerous trial mixtures explored based on the compressive strength and other essential behavior of the mixes
- To design and adopt a suitable mixture proportioning process for CWLB based on the evidence-informed decisions made from the preliminary laboratory work.

The various experimentations carried out included: determination of appropriate batching procedure for the constituent materials, mixing procedures, study of fresh CWLB mixtures, molding and compacting procedure, study of CWLB specimen, curing procedure and selection of efficient trial mix composition. The preliminary laboratory work revealed the following characteristics from the trial mixture:

- The colour of the fresh CWLB mixture
- The behavior of the fresh CWLB mixture
- The requirement for admixture and other processing parameters.
- It was also used to narrow down the number of the preliminary compositions, so that the most efficient ones were selected.

The details of the experimentation conducted, the findings and decisions made are reported in Chapter 4 of this thesis.

3.8 MAIN LABORATORY EXPERIMENTATION

The main laboratory experimentation was divided into four major phases. Phase one of the experimentation involved the study of the salient parameters that influence the compressive strength of the CWLB specimen produced from the initially selected trial mix composition.

The second phase of the main experimentation involved the optimization of the mix composition of CWLB using the factors/parameters identified for the purpose of determining the optimum combination of processing parameters and the corresponding optimum mix composition.

The third phase of the main experimentation involved the determination of the properties of CWLB specimen produced from optimal processing parameters. The properties tested includes; compressive strength, UPV, density, dimensional check/stability, capillary water absorption, thermal conductivity and reaction to fire.

The fourth phase involved the modelling and simulation of the compressive strength of the typical representative sample of CWLB using Abaqus CAE software for the purpose of determining the estimated crushing load and compressive strength of CWLB at different sizes.

3.8.1 PHASE 1: Study of Salient Parameters Influencing the Compressive Strength of CWLB

Being a relatively new material, many of the characteristics of CWLB are yet to be fully studied and understood. For instance, unlike concrete and papercrete which form paste in the fresh state due the inclusion of hydraulic cement in their constituents, experiences from the preliminary study shows that CWLB exhibits fibrous form in the fresh state as it was made from majorly inert/unreactive materials. Thus, adequate understanding of the salient parameters that affect its strength properties are important for processing and product optimization. Aside this, the outcome of the preliminary experimentation identified five trial mixes (out of a total of 79 trial mixes investigated) containing varying sand contents whose dimensional stability and density were satisfactory with regards to the requirements specified by BS EN 771-4 (2011) and BS EN 2028-1, (1975) for lightweight non-load bearing blocks but with corresponding low compressive strength. It therefore became paramount to maximize the compressive strength of the selected trial mixes to satisfy the standard requirement for non-load bearing lightweight blocks.

This study was therefore conducted to determine the effect of processing parameters which include; curing method, curing age, crushing orientation, water content, binder quantity, and compacting forces on the compressive strength of CWLB. Since this study was focused on identifying the factors that have crucial effect on the compressive strength of CWLB and not to study the interaction between the factors, the traditional one factor at a time (OFAT) approach (Montgomery, 2013) was adopted. The details and findings from this study are reported in Chapter 5 of this thesis.

3.8.2 PHASE II: Optimization of Mix Composition of CWLB

Based on the findings from the study of factor effects (i.e. findings from phase I) the processing parameters which include; Water/ binder ratio, WA/sand ratio, and compacting force were found to have the crucial effects on the compressive strength of CWLB. Therefore, for the purpose of maximizing the compressive strength of CWLB to satisfy the strength requirements for non-structural/non-load bearing blocks, this optimization study was conducted to determine the optimum mixture composition for CWLB. This aim was achieved by employing the Taguchi design of experiment (DOE) statistical optimization technique in conjunction with laboratory experimentation and ANOVA (Minitab software). The findings from this study are reported in detail in Chapter 5 of this thesis.

3.8.3 PHASE III: Determination of the Engineering Properties of CWLB.

Masonry blocks are expected to be tested for properties that usually influence their performance during application in building construction. Based on the recommendation of BS 771-4:2011 regarding the expected properties of block to be used for non-load bearing application, the CWLB specimen produced from the optimal processing parameters were subjected to test which includes: compressive strength test, bulk density test, capillary water absorption test and dimensional check, UPV, thermal conductivity, and reaction to fire. The detail result for each of the properties tested are presented and discussed in Chapter 6 of this thesis. In addition, findings from additional experimentation conducted to produce cement stabilized CWLB designated as stabilized wastepaper based lightweight block (SWLB) for the purpose of evaluating the effect of addition of cement on its properties was also presented in Chapter 6.

Having obtained optimum mix composition for CWLB, test specimens in the form of 50mm x 50mm x 50mm cubes and 50mm x 50mm x 30mm rectangular prism were made to determine its various engineering properties. The Table 3.6 shows the molds sizes, test, equipment, and reference standard codes utilized for this purpose. The detail procedures followed in accordance with the relevant standards are detailed in 3.8.3.1 to 3.8.3.8 of this chapter.

Table 3.6: Mold sizes and corresponding Tests

S/N	Test	Mold sizes(mm)	Equipment	Reference code
1	Compressive strength	50x50x50	Compression testing machine for mortar	BS EN 772-1 and BS EN772-6
2	Density	50x50x50	Scale and caliper	BS EN 772-13
3	Dimensional check	50x50x50	Caliper	BS EN 772-16
4	UPV			BS 12504-4:2004
5	Thermal Conductivity	50x50x30	Heat conduction Apparatus	BS EN 1745
6	Capillary Water Absorption	50x50x50	Capillary water Absorption equipment	BS EN 772-11
7	Flammability	50x50x30	Fire reaction apparatus	BS EN 13501-1
8	Elastic modulus	Estimated	Empirical formula	BS EN BS1881-203:1986 and BS EN 12504-4:2004

3.8.3.1 Compressive Strength

Compressive strength is defined as the masonry unit's ability to withstand an axially applied load, whether on the edge or the bed face of the block. It is also the average compressive strength of a test sample of ten blocks, and it is required that the weakest individual block must not be less than 80% of the average value.

Compressive strength is expressed mathematically as the ratio of maximum crushing load (N) to the [minimum surface area (mm^2). The specification for the compressive strength of masonry block differs for different; code, countries and for different application (see Table 3.7). The BS 771-4: 2011 which is among the EN771 series of code for masonry block recommended a minimum strength of 1.5 MPa for lightweight non-load bearing block unit to be used for partitioning/non-structural application. A minimum compressive strength at 28 days of 2.75 N/mm^2

is recommended for load-bearing walls, and 1.4 N/mm^2 (minimum) is specified for non-load-bearing walls by the Ghana Building Code (National Committee 1989). The range of standard strength specified by the Nigerian Building code (2006) and the Nigeria industrial standard (NIS) 587:2007 for load bearing blocks are respectively between 1.75 to 2.00 N/mm^2 and 2.5 N/mm^2 to 3.45 $N/mm^{2.}$ According to the BS 6073 (1981), the average crushing strength of 10 blocks of thickness 75mm or greater should not be less than 2.8 N/mm^2 and not less than 0.9 (crushing Strength + 0.62 S) where S is the standard deviation for the sample. The BS EN 771-3(2003) does not specify a minimum compressive strength of a unit but requires that the individual compressive strength of a unit must be at least 80% of the mean compressive strength(F_m) of 10 specimen and the unit express in MPa (N/mm^2)

Table 3.7: specification for compressive strength of Masonry block

Standard specification requirement			
Non-load bearing masonry block		**Load bearing masonry block**	
Average compressive strength (MPa)	Reference Code	Average compressive strength (MPa)	Reference Code
1.4	NZs42984798, (1998)	1.75 -2.00	Nigeria Building code (2006)
1.3	Ghana building code (1989)	2.5 - 3.45	NIS 587 (2007)
1.80	Pr EN 772-1(1992)	2.8	BS 6073, (1981)
1.5	BS EN 771-4:2011		

The compressive strength test for CWLB specimen was conducted in accordance with BS 772-1:2011 with the aid of a 250 KN sercomp7 hydraulic compression testing machine (Fig. 3.11) using a 50mm x 50mm x 50mm CWLB cubic block specimen. The specimen was centrally positioned with the centre of the ball seated platen on the compression testing machine. The compressive load was applied at a loading rate of 2400 N/s and the maximal crushing load achieved was recorded. The compressive strength was calculated by dividing the crushing load (FF) by the loaded area A (mm^2) as shown in equation (Eqn. 3.3). The average for the 3 specimen samples tested for each mix were recorded to the nearest 0.01 N/mm^2.

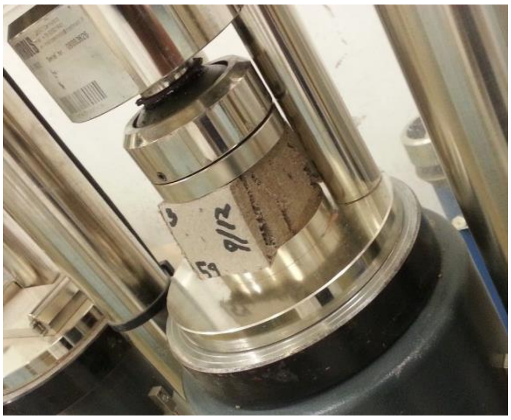


Fig. 3.11: C250KN SERCOMP7 hydraulic compressive strength machine.

$$Compressive\ Strenght = \frac{Crushing\ Load(N)}{Surface\ Area\ of\ specimen(mm^2)}$$ **----------------Eqn. 3.3**

3.8.3.2 UPV

The ultrasonic pulse velocity is a conventional non-destructive test method used for examination of the quality of construction, materials in terms of strength, porosity, cracks and defective microstructure. It principle of measurement involves the measurement of time required for an ultrasonic pulse to be transmitted through a specimen. The CWLB specimens were subjected to UPV test using the Proceq Pundit Lab instrument as shown in (Fig. 3.12). The UPV was determined using the expression shown in equation (Eqn. 3.4). The average value for 3 specimens were recorded to the nearest 1m/sec.

$$\boldsymbol{UPV = \frac{L(m)}{T(s)}} \quad \textbf{---Eqn. 3.4}$$

Where: L=thickness of sample (m), (i.e. length of transmission), T= Time required for ultrasonic pulse transmission through the specimen (sec)

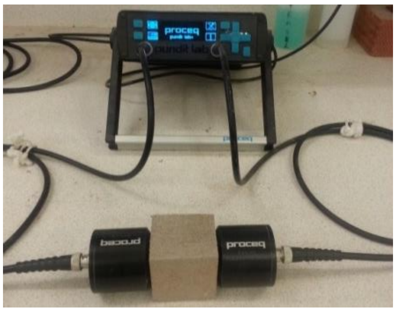


Fig. 3.12: Proceq Pundit Lab+ ultrasonic pulse velocity instrument.

3.8.3.3 Density

Density is defined as the measure of how many particles of an element of material are squeezed into a given space (Averill and Elderedge, 2007). The more closely packed the particles, the higher the density of the material. Higher levels, therefore, indicate a corresponding degree of compaction. It is the mass of the masonry unit divided by the dimensional volume, mathematically expressed as the ratio of mass of block (kg) to the ratio of dimensional volume of block (m^3). The BS EN 771-4:2011 noted that the net density of AAC masonry block (which in this study is regarded a reference lightweight non load bearing block) usually ranges from 300 kg/m^3 to 1000 kg/m^3. The BS EN 771-4:2011 recommend range of 300

kg/m^3 – 1000 kg/m^3 for lightweight non load bearing blocks while the BS 2028 (BSI 1975) recommends a maximum bulk density of 1,500 kg/m^3 and a minimum of 625 kg/m^3 for lightweight masonry block to be used for both load-bearing and non-load bearing applications. The density of the CWLB specimen was determined in accordance with the method specified by BSEN 772-13:2011 for determination of net and gross dry density of masonry units.

The specified procedure involved the air drying of the specimen to a constant mass and obtaining the net and gross volume followed by the calculation of net and gross dry density of the masonry units. Considering that the specimen used in this study are solid cubic specimen, a single determination and calculation of dry density was made. The specimen was weighed using a sensitive scale with precision of 0.01 g. The volume of the specimen was obtained by measuring the length , width and height with use of overlapping jaws caliper in accordance with BS EN 772 -16:2011 procedure. The density of the specimen was later calculated using equation (Eqn. 3.5)

$\rho = \frac{M}{V}$ ------------------- -------------------------------- Eqn. 3.5

Where:

ρ = Bulk density (Kg/m^3)

M= Mass of Specimen (Kg)

V= Volume of Specimen (m^3)

3.8.3.4 Dimensional check

Basically, the variations in the lengths, widths (thickness) and height of a samples should be within the tolerance limits specified in BS 2028 (BSI 1975), BS 6073(1981) and EN 771-4(2011) as shown in Table 3.8. An investigation by

(Bardein and Tuuli, 2004) revealed that the failure of most masonry blocks falling within the tolerance limits for the height are due to the manner in which the blocks are demolded, observing that, when the lever of the mold is pressed too slowly to release the fresh block, this leads to an extension in the height of the block. The second reason is the surface on which the blocks are stored. If the fresh masonry blocks are not stored on pallets or a well prepared leveled floor (preferably a floor finished in screed) but instead are stored on the bare floor, this leads to some soil collecting onto and forming part of the masonry block, thus causing an increase in the height of the block. Hence, all the precautions pointed out by the BS 2028:1975 were applied in order to achieve adequate dimensional stability. The dimensional check was carried out to determine the deviation of length L, width W and height H of CWLB specimen.

Table 3.8: Permissible dimensional deviation of Masonry unit in accordance with BS 6073(1981)

Dimension	Deviation
Length	+3 mm, -5 mm
Height	+3 mm, -5 mm
Thickness	+2 mm, -2 mm average individual +4 mm, -4 mm at any point

The test was conducted in accordance with procedure recommended in section 7.1 of BS EN 772-16:2011. The length, width and height for each specimen were determined by taking one measurement at the midpoint of each of the CWLB specimen using a measuring caliper with overlapping jaws (Fig. 3.13) and the results obtained are presented in chapter 7 of the this thesis.

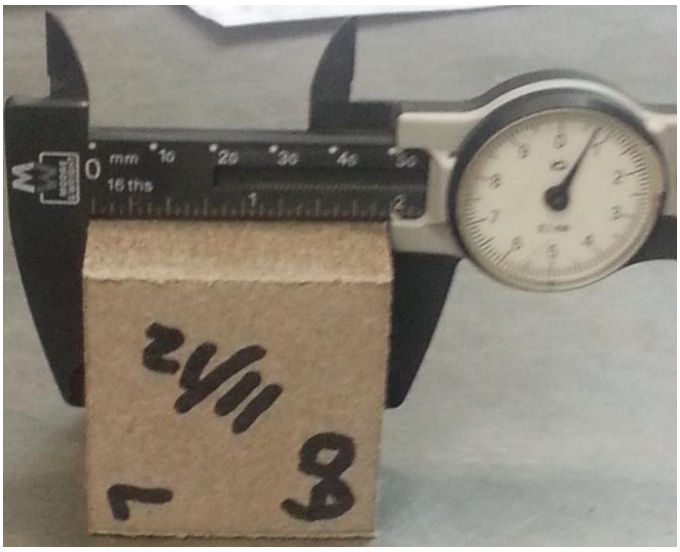


Fig. 3.13: A measuring caliper with overlapping jaws

3.8.3.5 Capillary water absorption

Capillary water absorption can be described as a phenomenon in which a material absorb liquid into the small opening with its microstructure, due to the intermolecular attraction within the liquid and the solid. Organic materials which includes; bricks, stone, tile plaster mortar and concrete are susceptible to water absorption as well as transmission by capillary action due to their porosity and permeability (Hall and Hoff, 2011; Karagiannis *et al.*, 2016).

The BS EN 771-4:2011 recommends that water absorption property be determined for masonry unit when relevant to its intended uses. Though CWLB is not designed for use where there is exposure to the weather elements, but being a novel lightweight block, it seemed appropriate to determine its coefficient of capillary absorption in other to make necessary recommendation for its installation in real life application. Therefore, the capillary water absorption test for CWLB was carried out in accordance with the method specified by EN 772-11:2011.

The BS EN 772-11:2011 give specification for the method to be used for determination of capillary water absorption coefficient of different types of masonry units which includes: aggregate concrete masonry units, autoclave aerated concrete masonry units, natural stone, and manufactured stone masonry units. The procedure specified involved drying of masonry unit to a constant mass and subsequent immersion of the face of the unit that will be exposed to the element during practical application in water for a predetermine or specified period of time followed by the determination of the increase in mass using relevant expression stated in the section 8 of BS EN 772-11:2011 as may be applicable. For the purpose of the CWLB, the expression specified for determining the coefficient of capillary water absorption for autoclave aerated concrete was adopted.

The CWLB specimen of size 50mm x 50mm x 50mm was dried to a constant mass (Mdry,s) in a ventilated oven at a temperature of 70 ^{o}C ± 5 ^{o}C. After cooling at room temperature, the measurements of the dimensions of the faces of the specimen to be placed in contact with water were taken and the gross area A_s for each specimen were calculated. The specimens were placed with their faces supported on a supporting device which has an area of 400 mm^2 in order to ensure partial immersion (Fig. 3.14). The specimens along with the supporting devices were immersed in water to a depth of 5mm ± 1mm throughout the duration of the test. The stopwatch was activated. As a precaution water level was maintained constant throughout the test duration and the tank was covered to prevent evaporation of wet specimen. The specimens were removed and weighed after immersion time period of 1-10 minutes respectively. Caution was taken to wipe off surface water from each specimen prior to weighing. The coefficient of water absorption due to capillarity action was determined to the nearest $1g/(m^2xs^{0.5})$ using the expression shown in equation (Eqn. 3.6)

$$C_{w,s} = \frac{M_{so,s} - M_{dry,s}}{A_s\sqrt{t_{so}}} \times 10^6$$ ------------------------------------ **Eqn. 3.6**

Where Cws= capillary water absorption coefficient

Msos= Mass of immersed specimen

Mdry= Dried Mass of Specimen

As= Gross area of Specimen

Tso= Time of immersion (sec)

The results are presented and discussed in chapter 7 of this thesis.

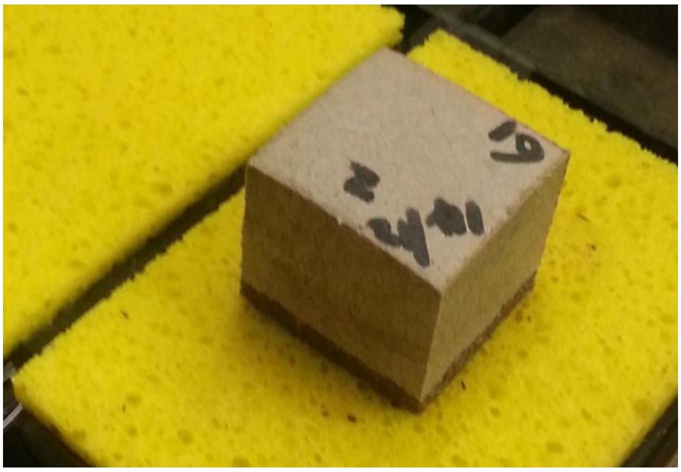


Fig. 3.14: Capillary water absorption equipment layout

3.8.3.6 Thermal conductivity

Thermal conductivity is the property of a material that determines its ability to conduct heat or otherwise. The thermal conductivity is not needed for the structural analysis of masonry structure; it is however needed to determine the insulation properties of the block. Because of the conditions that must be maintained inside the structure in which a block will be used as the case may be, the insulating properties value of the block should be such that can save energy costs. The thermal conductivity of a material is determined by measuring the coefficient of thermal conductivity K which is a measure of the rate of heat energy that passes perpendicular through a unit area of homogeneous material of unit thickness for a temperature difference of one degree and it is usually expressed in W/m.k (Asdrubali *et al.*, 2015). The BS EN 771-4 (2011) recommends that information should be provided on the thermal properties of masonry unit intended for use in an element subject to thermal requirement. This should be done in accordance to the procedure in BS EN 1745.

To measure the thermal conductivity of CWLB, a rectangular prism specimen of dimension 50mm x 50mm x 30mm was made from the OPTIMAL CWLB composition and for each of the weaker mixes. The experiment was carried out using the heat conduction apparatus (see Fig. 3.15 and Fig. 3.16) and the value of thermal conductivity was express in W/mk. According to Fourier's law of conduction, heat flow by conduction in a certain direction is proportional to the area normal to that direction and to the temperature gradient in that direction (see Eqn. 3.7a).

$$Q = \frac{KAdT}{dX} \qquad \text{-- Eqn. 3.7a}$$

Where:

Q= Heat supplied (W)

K=thermal conductivity

A=Area of specimen

dT/dX= temperature gradient

negative sign (-) + indication of heat flows in direction of decreasing temperature.

For steady state temperature, it is assumed that the heat energy input by an electrical heater enters at one end of a solid material and get dissipated from the other end in a uniform manner which means that the thermal conductivity of a specimen can be obtained using the expression in Eqn. 3.7b.

$\boldsymbol{K = \frac{QdX}{AdT}}$ **-- Eqn. 3.7b**

Q=Heat supplied (W)

dX=Distance between the hot and the cool surface of specimen

A= Area of specimen (m^2)

dT= temperature change (K)

Fig. 3.15: Heat Conduction apparatus for measuring Thermal Conductivity

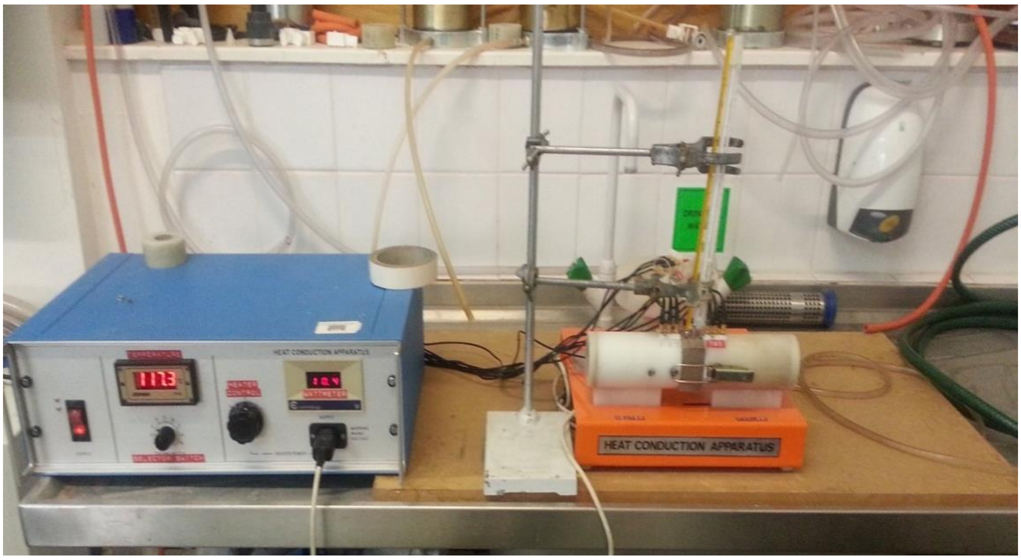


Fig. 3.16: Layout for measuring the thermal conductivity of CWLB specimen

3.8.3.7 Elastic modulus of CWLB

Modulus of elasticity is a property that measures the deformation of structural element of a building material. It is also a fundamental factor in determining the modular ratio n, commonly utilized for design of structural member subjected to flexures. Also, for a masonry structure design to adequately comply with serviceability specification, the knowledge of elastic modulus of a masonry unit is required for determination of elastic deformation due to first application of load and for estimating creep arising from sustained load (Brooks, 2014).

Many standard codes for masonry have formulated empirical formula for estimating the modulus of elastic for masonry in the absence of experimental results. ACI 530-92 (ACI, 1995) recommended the estimation of masonry modulus of elasticity (E_m) as the chord modulus of the linear part of the masonry compression stress-strain curve, which is typically defined to be between 5% and 33% of the ultimate masonry compressive strength (f'_m) (ACI 530,). Most standards including Eurocode 6 (CEN 2005), ACI 530, Canadian masonry code (CSA 2004), etc. expressed the relationship between compressive strength and modulus of elasticity of masonry as shown in equation (Eqn. 3.8);

$$\boldsymbol{E_m = k\, f'_m} \qquad \text{Eqn. 3.8}$$

Where k is a constant whose recommended value differs from one code to the other. Eurocode 6 recommended 1000; ACI 530 recommended 900; while CSA recommended 850 etc.

However, considering the fact that the constituent materials and mode of strength development of CWLB differs from that of masonry blocks, a different approach which takes into consideration the known properties CWLB was adopted to estimate its elastic modulus.

3.8.3.7.1 Estimation of Elastic modulus of CWLB using BS 12504-4:2004 Approach and Newton-Laplace Equation.

Due to the unavailability of required equipment for the determination of the stress-strain relationship for CWLB, the elastic modulus of CWLB was estimated based on the principle of ultrasonic pulse velocity testing described by BS 1881-203:1986 and BS 12504-4:2004 in conjunction with the Newton-Laplace acoustic theory. According to the above listed literatures, the velocity or speed of sound in a solid material (V) is proportional to the square root of the ratio of its modulus of elasticity (E) and its density (ρ) (Turgut, 2004). BS 1881-203 expression and the Newton Laplace Expression for velocity of sound in solid are indicated in equation (Eqn. 3.9) and (Eqn. 3.10a) respectively.

$$\boldsymbol{V^2} = \sqrt{\left(\frac{E}{\rho}\right)}$$ ---------------------- **(Eqn. 3.9**) Newton-Laplace equation

Where: V^2 is the ultrasonic pulse velocity of the solid material (i.e the velocity/speed of sound through the material in (m/s)), ρ is density of the material in (Kg/m^3), and E is the elastic modulus of the material in (MPa)

$$\boldsymbol{E_d = \rho V^2 \frac{(1+v)(1-2v)}{1-v}}$$ --------------------------------- (Eqn. 3.10a) BS 1881-203:1986

Where; E_d is dynamic elastic modulus (MPa), V is the ultrasonic pulse velocity (m/s), ρ is density of the material in (kg/m^3), and v is the poisson ratio.

According to Mavko *et al.*, (2009), poisson ratio v is equal to zero in linear elasticity of an isotropic homogeneous material in the sense that; the young modulus E is equal to the ratio of extensional stress to the extensional strain in a uniaxial strain condition and the P wave modulus (M) (indicated in Eqn. 3.11) is equal to the ratio of axial stress to axial strain in a uniaxial strain condition.

Therefore, assuming either a uniaxial stress or uniaxial strain condition, the equation (Eqn.3.10a) becomes equation (Eqn. 3.10b) as follows:

$\boldsymbol{E} = \boldsymbol{\rho V^2}$ -- (Eqn. 3.10b)

$\boldsymbol{M} = \boldsymbol{\rho V_p}^{\boldsymbol{2}}$ -- (Eqn. 3.11)

Where:

M= P wave modulus (MPa)

V_p = Ultrasonic pulse velocity (m/s)

Therefore, the equation (Eqn. 3.11) which is also equivalent to equation 4.10b was adopted to estimate the elastic modulus of CWLB. The findings are reported in Chapter 7 of this thesis

3.8.3.8 Reaction to fire

The BS EN 771-4:2011 recommends that the appropriate reaction to fire of masonry unit containing a mass or volume fraction of homogeneously distributed organic materials greater than 1.0% should be declared and classified in accordance with EN 13501-1 specification. The flammability of CWLB was tested to determine if it would be fuel in the event of a fire. A flame was applied to a CWLB sample and the ability of the sample to ignite and/or smolder was observed. The fire performance of CWLB was determined in accordance with the method specified by the BS EN ISO 11925-2:2010(E) for the classification of reaction to fire for all construction products including products incorporated within building elements. Also, the EN 13501-1 was followed for the classification of fire reaction. The specified procedure involves the determination of a specimen's ignitability by the application of direct small flame impingement under zero impressed irradiance on the test specimen in a vertical orientation.

A small matched sized flame with burning height of 2 mm was applied to the surface of the CWLB specimen for 15 sec and 30 sec. The specimen was tightly held vertically with the aid of specimen holder and clamp. The spread of small flame up the vertical surface of the specimen was observed and measured using a flame height measuring device. The filter paper place under was also observed for traces of flaming droplets and traces of ignition. As the flame was applied the stopwatch was activated to record the flame application period. The BS EN 11925-2 (2010) recommended an appropriate size specimen to be produced for the fire test for material with sizes less than the specified size. Therefore, rectangular prism block test specimen of 50mm x 50mm x 30mm was used for the test. Different exposure conditions were tested. The flame was applied to both the surface and the edge of the specimen separately in order to determine the worst exposure condition. Data which includes; the position of flame application, occurrence or non-occurrence of ignition, observation whether flame tip reaches 150 mm above the flame application point and the time it does, presence of flaming droplets or ignition of filter paper and the physical behavior of test specimen during test were carefully recorded. The record was used in conjunction with BS EN 13501-1 to classify the fire reaction of the specimen. This procedure was repeated for the entire specimen tested and the findings are reported in chapter 6 of this thesis

3.8.4 PHASE IV: Modelling and Simulation of Compressive Strength of Typical/Prototype Representative Sample of CWLB

In order to determine the crushing load for a typical field representative of CWLB, the simulation, and modelling of its compressive strength was conducted using Abaqus CAE software. The deformation properties (including; elastic modulus, density and assumed Poisson ratio) of the optimal CWLB 50mm x 50mm x 50mm size specimen obtained from the laboratory experimentations were used as input for the finite element modelling and simulation.

3.8.4.1 Basics of Finite Element Analysis of the Compression Process of CWLB in Abaqus CAE

The Finite Element Modelling analysis of insitu solid and hollow samples of CWLB in Abaqus CAE was carried out in alignment with the Finite Element Analysis procedures (Abaqus 6.13 online documentation, 2013; Banks *et al.*, 2010) by executing three major stages of processing viz; pre-processing, simulation and post-processing (Abaqus 6.13 online documentation, 2013c).

During the pre-processing stage, the proposed CWLB model was defined to represent/mimic the physical problem and an input file was created to that effect. Basically, as elaborated in Abaqus user guide (Abaqus 6.13 online documentation, 2013c), the pre-processing stage involved the;

1) Creation of the CWLB prototype model graphically (i.e. 3D nonlinear finite element model) in the part module of Abaqus CAE to represent the real physical problem.

2) Definition of the CWLB material properties and section properties of the real physical problem in the property module of Abaqus CAE (i.e. the incorporation basic material characteristic including: elastic modulus, density and the poison ratio of the CWLB optimal mix composition).

3) Assembling of the model (which may /may not contain several parts) in the assembly module of Abaqus CAE. This involved the assembling of CWLB model (which is a deformable 3D model) in between the top and the lower crusher/anvil (which are rigid bodies).

4) Configuration of the analysis procedure and output request (e.g. stress, Load and displacement) in the step module of Abaqus CAE

5) Application of loads and boundary conditions to the model (depending on the type of analysis and model features) in the load module of Abaqus CAE

6) Meshing of the model in the mesh module of Abaqus CAE

The simulation stage was carried out using the job module available in Abaqus CAE, during this simulation stage, the software utilizes the numerical problem that had been created during the pre-processing stage to create a job and the same was submitted for analysis. The processes that run in the background when a job is submitted is the main simulation. It can either be executed using Abaqus standard or Abaqus explicit.

The post-processing stage is the step taking to evaluate the result and come up with engineering judgements; this stage is usually executed using the visualisation module available in Abaqus CAE. The parameters evaluated for the solid and the hollow CWLB finite element models includes the crushing load and corresponding displacement on the model. The in-depth details of the analysis and the findings are presented and discussed in Chapter 7 of this thesis.

3.9 SUMMARY OF CHAPTER THREE

This chapter presented the research methodology and experimental programme that was followed to achieve the aim and objectives of this research. The preparation of materials, the processing of wastepaper to wastepaper aggregate, the parametric properties of the constituent materials of CWLB and the procedures employed were presented and discussed.

Under the parametric study, the constituent materials of CWLB which includes: WPA (utilized as major aggregate filler), Waste additive (utilized as binder), sand (utilized as additional aggregate filler), and clay (utilized as admixture) were examined based on the relevant/applicable British standards in order to determine their geometrical, physical and chemical properties. The essence of this was to assess; their expected behaviour during application, their compliance with standard requirements, and to ensure quality control as well as their suitability for the intended use. The results show that the WPA produced from post-consumer wastepaper belonged to the categories of lightweight artificial aggregate in terms of its density and specific gravity, and can be classified as fine graded aggregate in terms of its granulation. Other materials including the sand, clay sample also displayed normal characteristics. The chemical composition obtained for the waste additive indicates its suitability as binder and its inert characteristics. These findings served as a basis for the combination/proportioning of constituent materials and the design of trial mixes for CWLB.

The research design and procedures employed for the main experimentaion, the standard specification referenced and the rationale for same were discussed. The next chapter (Chapter 4) will present the details and the findings from the preliminary laboratory experimentation conducted to develop a viable manufacturing technology for CWLB.

CHAPTER FOUR: PRELIMINARY STUDY FOR MIXTURE PROPORTIONING OF CWLB

4.1 INTRODUCTION

This chapter presents the details of preliminary laboratory experimentation conducted to determine a suitable mix proportioning process for it. The various processing parameters explored for decision-making include:

- Batching method
- Trial mix compositions
- Mixing method
- Particle size of Wastepaper aggregate (WPA)
- Test specimen size
- Molding/compaction method
- Curing method
- CWLB mixture properties

4.2 BATCHING OF CONSTITUENT MATERIALS

The processes for the development of mix proportioning for CWLB started with the consideration of a suitable batching method for the constituent materials, this is because in masonry technology, production of either mortar or masonry block usually starts with proportioning of constituent material either by volume of by weight (Kreh, 2014a). For large masonry block production, batching of constituent material is achieved through subjection of same into a scale for weighing and measurement, this procedure ensures uniformity across different batch of mixes and resulting block units (Kreh, 2014b).

To determine the suitable batching method for CWLB, predetermined equivalent quantities of WPA, sand, and waste lactose were weighed on the laboratory scale, the volume occupied and the weight exhibited by each of the samples were measured and recorded for comparison. It was found that, at equivalent volume of samples, WPA exhibited lighter weight compared to sand sample and (waste additive) lactose sample. Similarly, WPA occupied higher volume compared to the corresponding sand and lactose samples at equivalent sample weight. Therefore, considering the observed wide variation in the physical properties of constituent materials (as apparent from their measured specific gravity and loose bulk density) and the need to achieve accurate proportioning of constituent materials, it was decided to observe the procedure of batching by weight in all further experimentation. Similar approach was employed by Akinwumi *et al.*, (2014) as a batching procedure for constituent materials of papercrete blocks.

4.3 DESIGN OF TRIAL MIXES FOR CWLB

In order to determine a suitable mix composition for the CWLB block, numerous trial mixes were designed and prepared from mixtures of WPA, sand, binder, water and natural admixture (i.e. clay) (Fig. 4.1). All constituent materials were measured with respect to WPA because it occupied a major percentage in the designed mixes and also the peculiarity of its properties.

A total of 79 trial mixes were made from varied combinations of WPA/sand ratios, WPA/binder ratios, and water-binder ratios. The approach of trial mix batches was adopted because, several researchers in the literature; Hardjito *et al*., (2004), Bartojay and Halczak, (2010) had previously employed a similar approach for the development of mixture proportioning for novel building materials. As summarized in Table 4.1 and as subsequently presented in Appendix 1 (Table Apx. 1.1, Table Apx. 1.2, Table Apx. 1.3 and Table Apx. 1.4) four batches of trial mixes were designed and prepared.

Fig. 4.1: Constituent Materials of CWLB

The batches were designated as; Trial mix 1 (TM1), Trial mix 2 (TM2), Trial mix 3 (TM3), and Trial mix4 (TM4) respectively. Each group of Trial mixes in ascending order was designed as an improvement over the previous mix (in terms of proportion of constituents, water to binder ratio, and strength development). The corresponding trial block specimens for TM1, TM2, TM3, and TM4 were designated as; Trial Specimen 1 (TS1), Trial Specimen 2 (TS2), Trial Specimen 3 (TS3) and Trial Specimen 4 (TS4) respectively.

Table 4.1: Detailed summary of trial mixes

Trial Mix Batches No	Trial Mix Batches ID	Trial Specimen ID	Range of percentage Sand content (% by wt. of WPA)	Range of percentage binder content (% by wt. of WPA)	Range of Water/Binder ratios	Range of WPA particle size range	Method of Molding	No of Mixes
1	TM1	TS1	0% - 200%	100% - 300%	N/A	4mm-0.125mm	T	15
2	TM2	TS2	0% - 20%	0% -20%	10 - 50	4mm-0.125mm	T	36
3	TM3	TS3	0% -20%	20%	10	4mm-0.125mm	HP	14
4	TM4	TS4	0% -20%	20%	3.75	1mm -0.063mm	HP	14

Note: T = Tamping, HP=hydraulic Press

4.4 MIXING

Sufficient mixing is required to ensure adequate distribution of each of the constituent materials. Mixing of CWLB's constituent materials was carried out in a portable mortar mixer. The mixtures made from varied combinations of WPA, sand, binder, water and natural admixture and constant quantities of admixture (i.e. 5% clay) were thoroughly mixed together in the mixer for 20 minutes until consistency was achieved.

(A) CWLB Mixture with high mixing water

(B) CWLB Mixture with low mixing water

Fig. 4.2: Effect of mixing water quantity on CWLB mixture consistency

It was found that the fresh mixture of CWLB was greyish/ash in colour (due to the ink present in the recycled old newsprint (ONP)), and was fibrous. The amount of water in the mixture played an important role on the behaviour of fresh CWLB during mixing. When the mixing time was long (27 minutes), mixtures with high water content practically remain coarsed (see Fig. 4.2), inadequate compaction along with draining of excess water was observed during molding. This phenomenon was usually followed by low compressive strength of hardened CWLB, unlike papercrete whose compressive strength is reported not to be affected by neither water content (Kelly Hart, (Greenhomebuilding.com)) nor water to binder ratio (Yun *et al.*, 2007; Nepal and Aggarwal, 2014). However, CWLB mixtures with low water content became almost fluffy (see Fig. 4.2) at long mixing time with an attendant high degree of compaction and absence of draining water (excess water) during molding as well as high compressive strength of hardened specimen. To this end, it appeared that the mixing procedure for CWLB is different from the mixing procedure reported for papercrete in the literature (Fuller *et al.*, 2006b; Fuller, 2014) in terms of mixing water content. From the preliminary work, it was decided to observe long mixing time (27 minutes) for the preparation of CWLB mixture in all further studies and the effects of water content in the mixture was identified as test parameters in the detailed study. The following sequence of mixing was observed in all further studies:

- Measuring out (predefined quantity) and mix all the dry constituent materials in the respective order of WPA, sand, clay, followed by the addition of mixing water prior to the addition of binder (i.e. waste lactose)
- Rubbing in the liquid constituent sufficiently prior to feeding into the mixer.

- Mixing the mixtures together sufficiently for a period of 27 minutes in a mortar mixer prior to the commencement of molding.

4.5 TEST SPECIMEN FOR CWLB

Blocks used for wall construction are available in different sizes, shapes, and forms. However, for laboratory testing, the BS EN 771 series permits the use of smaller representative block test specimen samples as long as consistency is ensured. In order to minimize material consumption in this experimentation, cubic block specimen of sizes 50mm x 50mm x 50mm (Fig. 4.3) were molded to test for the quality of CWLB. The stepwise processes involved in the production of the test specimen included: batching/measuring out of constituent by weight, mixing, molding and curing. This size and shape of specimen was considered based on the recommendation of BS EN 772-1:2011 (Section 7.1) and BS EN 771-4:2011, that cubic specimen could be used as representative sample for testing of masonry block.

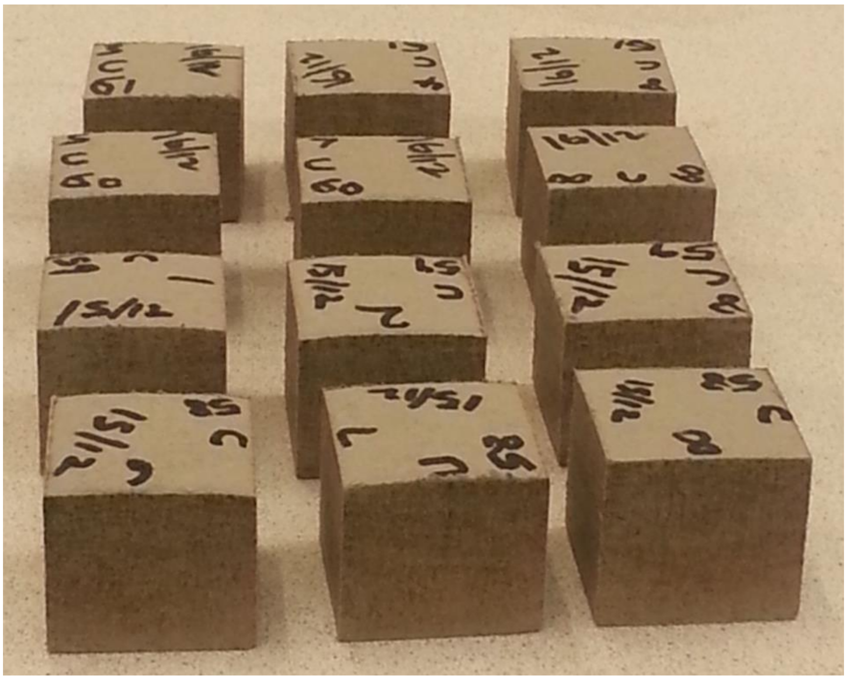


Fig. 4.3: 50mm x 50mm x 50mm CWLB cubic specimen

Also, a similar approach was used by Akinwumi *et al.*, (2014) for specimens used in evaluating the structural properties of papercrete recommended for use as hollow and solid blocks.

4.6 COMPACTION/MOLDING OF CWLB SPECIMEN

Compacting force in this experimentation refers to the quantity of mechanical energy applied to the CWLB trial mixtures scooped in a mold to produce a suitably compacted block specimen. According to Krishna Reddy (2002), the different methods available for compacting soil include; tamping, kneading, vibration and static load compaction. Therefore, considering the fact that the material under study is new and no standard specification is in place regarding a particular suitable compaction method for molding it, trial experiments were conducted to identify a suitable molding method. Two types of molding methods which include; tamping and static load compaction (using a hydraulic press) were explored in this study. The various trial experimentations conducted revealed the following:

- The tamping method could not produce suitable block specimen from either mixture containing low mixing water or mixture containing high mixing water. The pressure generated through tamping appeared inconsistent due to human error and was not sufficient to mold the specimen for a mixture containing low mixing water and the resulting specimen was not a true representative sample of CWLB specimen. This finding is similar to the research evidence from masonry block manufacturing technology; tamping method has been reported to be ineffective for the production of suitable block specimen due to its inability to consolidate fresh block mixtures properly and thereby leading to the production of block of unacceptable strength (Baiden and Asante, 2004). Specimen produced from mixtures containing high water content using the same method exhibited an unacceptable level of shrinkage at 28 days curing age due to the excess mixing water.

- The static load compaction (using a hydraulic press) method was able to produce suitable block specimen for both the mixture containing low and high mixing water with no apparent volume change of the specimen at 28 days curing age despite the fact that excess mixing water was seen draining out of the mixes containing high mixing water during molding. This method enabled the application of equivalent pressure to each and every specimen thereby producing a true representative sample of CWLB specimen. The pressure produced by the hydraulic press was adequate to produce suitable specimens from mixes containing low mixing water.

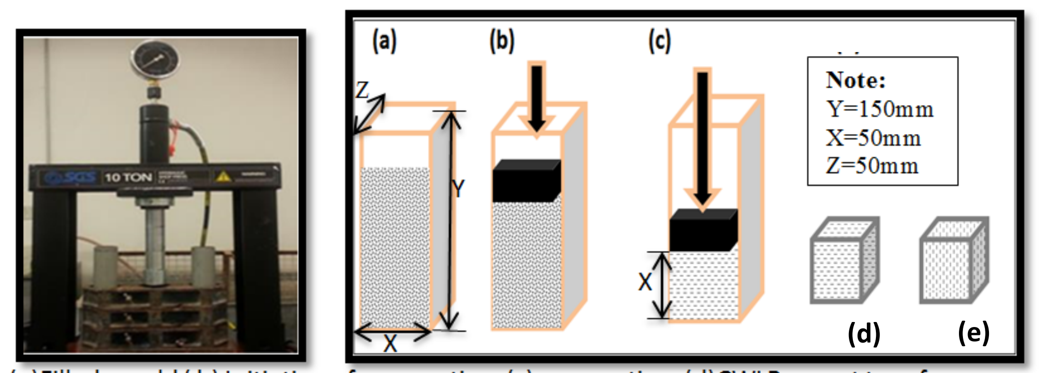
It was therefore decided to observe the procedure of using hydraulic press for molding of CWLB in all further experimentation. This method is similar to the method reported in the literature for molding of papercrete block (Fuller, 2014; Papercrete block press, 2013; Akinwumi *et al.*, 2014) and it also represents a true depiction of the technology/procedure being practiced in the field for molding masonry block and a practicable method that could aid the acceptance of the CWLB by the relevant stakeholders upon successful development. The following procedure was employed for molding of the specimen using the hydraulic press.

4.6.1 Procedure for Molding of Specimen

A predetermined quantity of the mixture was weighed and filled into the 50mm x 50mm x 150mm mold. To produce the cube block specimen, a 10 ton-capacity manual hydraulic press which has a pre-installed pressure measuring gauge was used to compress the mixture against the other end of the mold to form the required 50mm x 50mm x 50mm cubic CWLB specimen.

The 50mm x 50mm x 150mm mold was initially utilised to cater for the fibrous and the voluminous nature of the mixture (see Fig. 4.4). This approach is similar to that employed by Zavala (2013) in which he used a mold size of 645 mm to accommodate the voluminous nature of a 9.5 kg lean dry papercrete mix (containing paper crumble, OPC, sand and ash) and compressed the same down to a block size of 215 mm height (Zavala, 2013). This indicates that voluminous characteristics are a common phenomenon in cellulose mixes containing minimal water content.

The amount of compacting force employed in compressing the mixture was 2.5 metric tons which is equivalent to a compacting pressure of 9.807 MPa. This process was repeated for all CWLB specimens produced. However, the effect of compacting force on the compressive strength of CWLB was identified as a test parameter in the detailed study.



(a)Filled mould (b) Initiation of compaction (c) compaction (d)CWLB as cast top- face orientation (e) CWLB as cast side- face orientation

Fig. 4.4: Manual hydraulic press and schematic of CWLB compaction/molding process.

4.7 CURING

In masonry block production, curing of block specimens is usually done in open air for 28 days, prior to application. Curing in ambient laboratory temperature for 28 days prior to testing was adopted for the CWLB specimen, considering the fact that it could be demolded and handled right out of mold in the wet state. This observation is similar to the behaviour of freshly molded papercrete block produced using hydraulic press. Fuller (2014) reported that pressed papercrete block can be handled after demolding. However, considering the apparent average ambient temperature of 20 ^{o}C that was used (being a low temperate region) the effects of curing temperature on the compressive strength of CWLB was identified as test parameters in the detailed study. Also, for the purpose of determining the strength development with age, the effect of curing ages on the compressive strength of CWLB was additionally identified as test parameter in the detailed study.

4.8 TESTING OF CWLB TRIAL SPECIMEN

To simplify the process of selecting an efficient mix composition for the CWLB, compressive strength was initially considered as the benchmark parameter, this is due to the intrinsic importance of compressive strength in the structural design of concrete structures (Neville,1995) and its recommendation as an important property for consideration in the development of mixture proportioning process (BS EN 5328-2:1997). Therefore, tests which include; compressive strength test, dimensional check, density were conducted on the CWLB specimens using the applicable British standard procedures described in Chapter 3 of this thesis for each of the tests respectively. Other important properties of the block which includes; water absorption, fire resistance, thermal conductivity and flexural strength were exempted at this stage to be considered during the main experimental investigation on CWLB.

4.9 FINDINGS FROM TRIAL EXPERIMENTATION CONDUCTED ON TRIAL SPECIMEN

The summary of the findings obtained from the various trial experimentation conducted on CWLB are listed below, the detail discussion of same along with the evidence-informed decisions made are presented in Appendix 1 of this thesis. The various trial experimentations conducted revealed that:

- the waste additive was effective as binder for CWLB,
- the incorporation of mixing water and natural admixture play a significant role in the production of suitable and efficient CWLB specimen,
- the use of adequate proportion of sand relative to WPA is important for production of stable CWLB specimen,
- CWLB mixture is fibrous in the fresh state and exhibits characteristic similar to that of densified biomass during compaction,
- WPA particle size play a major role in the degree of compaction of CWLB specimen,
- WPA particle size play a vital role in the amount of mixing water required to produce workable CWLB mixture.

4.10 CRITERIA FOR SELECTION OF THE EFFICIENT TRIAL MIX COMPOSITION

The outcome of CWLB trial experimentation and the evaluation of the same against the specification of BS EN 771-4:2011 and BS 6073-1:1981, regarding permissible dimensional change and density of masonry block was critically observed. The criterion for selection of the initial trial mix composition of CWLB was optimized to include the dimensional stability and the density of the block specimen, in addition to the compressive strength which was initially considered as the benchmark parameter.

Compressive strength is one of the major properties that is usually employed to ascertain the quality and suitability of masonry blocks for the intended application, the BS 5328-2 (1997) (section 2.1) identified compressive strength as a benchmark parameter for selection of mix composition in concrete. Aside from this, the importance of dimensional stability of a masonry block cannot be overemphasised as it enables optimal use of units during wall construction, the BS 6073-1(1981) imposes a limit on the permissible/allowable dimensional change in a masonry block. Also, the BS 771-4:2011 noted that the density of lightweight non-load bearing blocks (e.g. AAC block) usually ranges from 300 kg/m^3 to 1000 kg/m^3 and the BS 2028, (1975) also specified the range of required density for masonry block to be categorized as a lightweight non-load bearing block.

The specifications are as follows:

- "Strength testing shall form an essential part of the assessment of conformity of concrete to standard specification" BS 5328-2 (1997) (section 2.1)."
- "The maximum allowable dimensional deviations for masonry blocks measured in accordance with Appendix A of BS 6073-1: 1981 shall be ;either +3 mm or -5 mm for the length, either +3 mm or -5 mm for the

height, and either +2 mm or –2 mm average or +4 mm –4 mm at any individual point for the thickness" (BS 6073-1,1981)"

- BS 2028 (BSI 1975) recommends a maximum bulk density of 1,500 kg/m^3 and a minimum of 625 kg/m^3 for lightweight aggregate block to be used both as the load-bearing and non-load bearing masonry blocks.

4.10.1 Selected Efficient Trial Mix Compositions of CWLB

Table 4.2 presents the initial CWLB trial mix composition selected to continue with the main experimentations. Based on the results, five mixes which contained 36, 40, 44, 48 and 52% sand content by weight of WPA and constant water/binder ratio of 3.75 were selected at the end of the trial experimentation as they were found to satisfy the criteria regarding density and the dimensional deviation (as highlighted in section 4.10). The compressive strength of the selected trial mixes which appeared low at this stage were subjected to improvements/ maximization through the optimization of the mix composition of CWLB (see Chapter 5)

Table 4.2: CWLB Trial mix composition selected from preliminary study

Mixture Details						Properties		
Mix No.	**Mix ratio WPA : S : B**	**Percentage Sand content (% by wt. of WPA)**	**Percentage Binder content (% by wt. of WPA)**	**Water /binder ratio**	**Natural admixture (% by wt. of WPA)**	**Compressive strength (MPa) (28days)**	**Density (kg/m^3)**	**Dimensional deviation of: Length, width and Height (mm)**
1	1: 0.36: 0.2	36	20%	3.75	5%	0.67	626.5	+0.5mm, +0.5mm and -1.5mm
2	1: 0.40: 0.2	40				0.50	636.3	
3	1: 0.44: 0.2	44				0.50	627.4	
4	1: 0.48: 0.2	48				0.52	650.0	
5	1: 0.52: 0.2	52				0.64	696.1	

4.11 DESIGNED MIXTURE PROPORTIONING PROCESS FOR CWLB

Based on the experiences gained during the preliminary experimental work and the evidence-informed decisions made from findings of preliminary laboratory work along with knowledge acquired from the limited past research on papercrete production available in the literature, the mix proportioning process shown in Fig. 4.5 was designed and adopted for the processing of CWLB

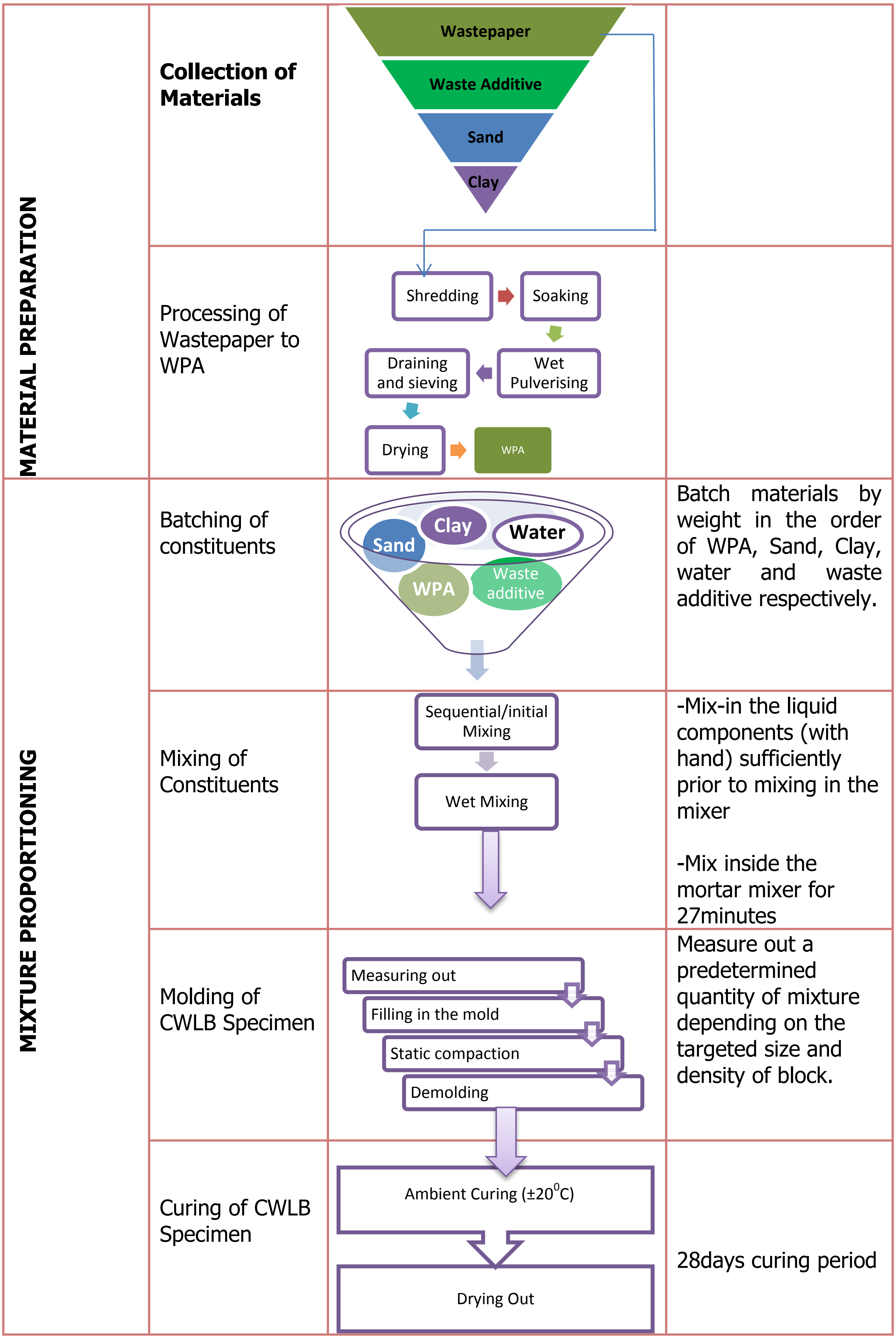


Figure 4.5: Designed mixture Proportioning process for CWLB

4.11.1 Protocols for the Mixture Proportioning Process of CWLB

The detailed protocols for the designed mixture proportioning process presented in Fig. 4.5 is presented below.

A) **Material preparation:**

(i) Shred wastepaper (using a cross cut shredder).

(ii) Soak the shredded wastepaper in water inside a bucket for 4 days.

(iii) On the 4^{th} day, drain water from the soaked waste paper using a sieve followed by gentle squeezing with hand to remove excess water.

(iv) Transfer the wet shredded wastepaper into a mixer (e.g. mortar mixer).

(v) Allow to mix for 20 minutes.

(vi) Remove from mixer and drain any excess water by squeezing with hand lightly.

(vii) Sieve with a 6.3 mm BS sieve size to obtain regular granulation

(viii) Spread on a tray and place in the oven.

(ix) Dry at 75 ^{o}C temperature for 4 days or until constant weight is achieved.

B) **Batching**:

(i) Depending on mix composition, weigh predetermined quantities of the dry constituent materials (i.e. WPA, sand and natural admixture) into a bowl in the order of WPA, sand and natural admixture respectively.

(ii) Weigh predetermined corresponding quantities of the wet constituents (i.e. water and waste additive) into two separate bowls each.

C) **Mixing**:

(i) Mix the water into the dry constituents and massage with hand to ensure even distribution.

(ii) Then mix the waste additive into the constituents and massage with hand again to ensure even distribution across the mixture.

(iii) Transfer the mixture into a mixer (e.g. mortar mixer) and mix for 27 minutes (or until the mixture turns almost fluffy).

D) **Molding**:

(i) Measure a predetermined quantity of the mixture (depending on the targeted block size and density).

(ii) Scoop or pour the measured fresh mixture into the mold (ensuring no loss) (note; due to the voluminous nature of the mixture, use a mold whose height is 3 times its width).

(iii) Mold the block with aid of a hydraulic press using the required amount of molding pressure.

(iv) Demould the block specimen upon removal from the press.

E) **Curing**: Place the demoulded specimen in the open air (at ambient condition) to dry/cure for 28 days.

4.12 SUMMARY OF CHAPTER FOUR

This chapter presented the details of the preliminary experimentations conducted to determine its mix proportioning process. It covered the procedure used in the determination of a suitable mix proportioning process for the development of CWLB (which represent the first objective of this research). Considering the novelty and the peculiar constituent of CWLB, a trial mix batches method was adopted to develop the process of manufacturing of CWLB with as much simulation of similar technology currently being used for masonry block production as possible. In order to minimize the number of variables in the trial and error approach, the wastepaper used for the production of WPA was limited to old newsprint (ONP) and the other constituents were obtained at one batch. After the various challenges encountered were surmounted through implementation/application of scientific knowledge/ideas from literatures, several evidenced informed decisions were taken on the processing parameters to address the peculiarities associated with the CWLB mixture. At the end, the trial mix batch method yielded five (5) efficient initial mix compositions (out of the 79 trial mixes tested) which were adopted to continue with the main experimentation. Also, a viable design of mix proportioning process for manufacturing CWLB was developed.

CHAPTER FIVE: RESULT, ANALYSIS AND DISCUSSIONS

5.1 INTRODUCTION

In this Chapter, the results obtained from the study of salient parameters influencing the compressive strength of CWLB and the results obtained from the optimization of CWLB mix composition are presented and discussed.

In Section 5.2 of this Chapter, the effects of various processing parameters on the compressive strength of CWLB are discussed. Each of the compressive strength test data plotted in Figures or given Tables corresponds to the mean value of the compressive strengths of three test CWLB cubes block specimens. The standard deviations are plotted on the test data points as the error bar. The parameters considered are as follows:

1. Curing ages
2. Water content
3. Binder quantity
4. Compacting force
5. Curing temperature
6. Crushing orientation

In all cases, WPA type C (i.e. passing BS sieve 3.35 mm) was used as decided from preliminary experimentation. Each of the constituent materials were batched by weight and measured relative to WPA. Static compaction with the aid of hydraulic press was used for molding of CWLB specimen.

On the other hand, Section 5.3 presents the details of the optimisation study conducted on CWLB and its findings.

5.2 FACTORS INFLUENCING THE COMPRESSIVE STRENGTH OF CEMENT-LESS WASTEPAPER BASED LIGHTWEIGHT BLOCK (CWLB)

The exploratory study conducted to develop the mixture proportioning process for the CWLB established that, five trial mixes (out of a total of 79 trial mixes investigated) containing varying sand content by weight of WPA (Table 5.1a) produced CWLB specimen that possessed desirable properties in terms of dimensional stability and density as specified by the BS EN 771-4 (2011) and BS EN 2028-1, (1975) for lightweight non-load bearing blocks. However, there is a need to maximize the compressive strength of the selected trial mixes to satisfy the standard requirement for non-loadbearing lightweight blocks which BS771-4: 2011 recommended to be a minimum of 1.5 MPa. Also, the optimum for other processing parameters of the trial mixes which includes; water/binder ratio, water content, curing, compacting pressures needs to be identified for the purpose of optimization of CWLB mixture composition. Thus, this study was conducted to investigate the effect of factors which includes; curing durations, water content, binder quantity, compacting forces, crushing orientation and curing temperature/method on the compressive strength of CWLB. The outcome of this study facilitated the identification of crucial processing parameters that were considered for the maximization of the compressive strength of CWLB and the corresponding optimization of its mixture composition.

Table 5.1a: CWLB Trial mix composition selected from exploratory study

Mix No.	WPA/sand ratio	Sand content (% by weight of WPA)	Binder content (% by weight of WPA)	Water content (% by weight of WPA)	Natural admixture (Clay) (% by weight of WPA)	Ave. Compressive strength (MPa) (at 28days) (n=3)	Density (kg/m^3)	Dimensional deviation of: Length, width and Height (mm)
M1	2.78	36%	20%	75%	5%	0.67	626.5	+0.5mm,+0.5mm and -1.5mm
M2	2.50	40%				0.50	636.3	
M3	2.27	44%				0.50	627.4	
M4	2.08	48%				0.52	650.0	
M5	1.92	52%				0.64	696.1	

5.2.1 Experimental Procedure

Since this study was focused on identifying the factors that have crucial effect on the compressive strength of CWLB and not the interaction between the factors, the traditional and well-established one factor at a time (OFAT) approach (Montgomery, 2013) was adopted.

5.2.1.1 One factor at a Time (OFAT) Method

The one-factor-at-a-time (OFAT) method is a conventional method of experimental design which entails the testing of factors, or causes, one at a time as an alternative to testing of multiple factors simultaneously. It involves the selection of a baseline starting point for each factors or (baseline set of levels for each factors), followed by a successive variation of each factor over it range with the other factors held constant at the baseline level (Montgomery, 2013). According to research evidence, OFAT approach is capable of concentrating investigation in areas likely to contain the optimum (Frey and Wang, 2006).

5.2.1.2 Mix Proportioning for Investigation of Different Factors

In order to simplify the experimentation at this stage, two series of mixes (namely series 1 and series 2) were designed from the two primary CWLB trial mixes (obtained from the preliminary experimentation) designated as mix M1 and M5. As shown in Table 5.1a, Mix M1 and Mix M5 contained the lowest and the highest sand content by weight of WPA (i.e. 36% and 52% sand content) and were hence adopted in this study as respective baseline mix composition for series 1 and series 2 to investigate the effect of different factors on the compressive strength of CWLB. A detail summary of the group of mixes contained within series 1 and 2 are presented in Table 5.1b.

As can be appreciated from Table 5.1a, other parameters which include; 20% binder content (measured by weight of WPA), 75% water content (measured by weight of WPA), and 5% natural admixture (measured by weight of WPA) were constant for each of the two mixes. The details of the mixture proportioning made to investigate the effect of; curing ages, water content, binder quantity, and compacting forces on the compressive strength of CWLB using mixes M1 and M5 are presented in Tables 5.2 and 5.3.

As shown in Table 5.2 and 5.3, the effect of curing durations was investigated by comparing the 7, 14, 21, 28, 60 and 90 days compressive strength of CWLB specimens.

Table 5.1b: Detail summary of group of Mixes contained within Series 1 and Series 2.

Series Number	Baseline Mix	Group ID	Factors investigated	Variation
Series 1	M1	Group M1A	Curing duration	7, 14, 21, 28, 60, and 90 days
		Group M1B	Water content	75%, 60%, 45%, 30%, and 15% (by wt. of WPA)
		Group M1C	Binder quantity	20%, 40%, 60%, and 80% (by wt. of WPA)
		Group M1D	Compacting Forces	2.5, 3.0, and 3.5 metric ton
		Group M1E	Curing temperature	Ambient (20^0C) and Oven (30^0C)
		Group M1F	Crushing orientation	As-cast top-Face(TF), and As-cast side-face (SF)
Series 2	M5	Group M5A	Curing duration	7, 14, 21, 28, 60, and 90 days
		Group M5B	Water content	75%, 60%, 45%, 30%, and 15% (by wt. of WPA)
		Group M5C	Binder quantity	20%, 40%, 60%, and 80% (by wt. of WPA)
		Group M5D	Compacting Forces	2.5, 3.0, and 3.5 metric ton
		Group M5E	Curing temperature	Ambient (20^0C) and Oven (30^0C)
		Group M5F	Crushing orientation	As-cast top-Face(TF), and As-cast side-face (SF)

The effect of water content was investigated by varying the water content of CWLB mixture composition from 75% (measured by weight of WPA) to 15% (measured by weight of WPA) at a 15% equal interval while all other parameters were held constant except the moisture content. The effect of binder quantity was investigated by varying the binder content of CWLB mixture from 20% (measured by weight of WPA) to 80% (measured by weight of WPA) at 20% equal interval. Other parameters were held constant except water content, (considering that the waste additive being utilized as binder is in liquid form) and the corresponding water content was for each of the binder quantities adjusted in such a way that all mixes tested had equal moisture content (i.e. waste additive + water content). The effect of compacting forces was investigated by molding the CWLB at three different compacting forces viz 2.5, 3.0 and 3.5 metric ton (i.e. 9.8 MPa, 11.8 MPa and 13.7 MPa respectively).

Table 5.2: Details of mix proportioning for Series 1 (mix M1 containing 36% sand content)

SERIES 1											Illustration for crushing orientation
Factors Investigated	**Group ID**	**Sand content (% by wt. of WPA)**	**Binder content (% by wt. of WPA)**	**Water content (% by wt. of WPA)**	**Fluid content (% by wt. of WPA)**	**Natural admixture (% by wt. of WPA)**	**Compacting Force (metric ton)**	**Curing temperature/ Method**	**Curing ages (days)**	**Crushing orientation**	
Curing ages	Group M1A	36	20%	75%	95%	5%	3	Ambient	**7**	As cast side	See Figure 5.8A
		36	20%	75%	95%	5%	3	Ambient	**14**	As cast side	
		36	20%	75%	95%	5%	3	Ambient	**21**	As cast side	
		36	20%	75%	95%	5%	3	Ambient	**28**	As cast side	
		36	20%	75%	95%	5%	3	Ambient	**60**	As cast side	
		36	20%	75%	95%	5%	3	Ambient	**90**	As cast side	
Water content	Group M1B	36	20%	**75%**	95%	5%	3	Ambient	28	As cast side	
		36	20%	**60%**	85%	5%	3	Ambient		As cast side	
		36	20%	**45%**	65%	5%	3	Ambient		As cast side	
		36	20%	**30%**	55%	5%	3	Ambient		As cast side	
		36	20%	**15%**	35%	5%	3	Ambient		As cast side	
Binder quantity	Group M1C	36	**20%**	75%	95%	5%	3	Ambient	28	As cast side	
		36	**40%**	55%	95%	5%	3	Ambient		As cast side	
		36	**60%**	35%	95%	5%	3	Ambient		As cast side	
		36	**80%**	15%	95%	5%	3	Ambient		As cast side	
Compacting force	Group M1D	36	20%	75%	95%	5%	**2.5**	Ambient	28	As cast side	
		36	20%	75%	95%	5%	**3.0**	Ambient		As cast side	
		36	20%	75%	95%	5%	**3.5**	Ambient		As cast side	
Curing temperature	Group M1E	36	20%	75%	95%	5%	3	**Ambient (20^0C)**	28	As cast side	
		36	20%	75%	95%	5%	3	**Oven (30^0)**		As cast side	
Crushing orientation	Group M1F	36	20%	75%	95%	5%	3	Ambient	28	**As cast Top Face**	See Figure 5.8A
		36	20%	75%	95%	5%	3	Ambient		**As cast side Face**	See Figure 5.8B

Note: Fluid content = binder content + water content

Table 5.3: Details of mix proportioning for Series 2 (mix M5 containing 52% sand content)

SERIES 2											**Pictorial Illustration for crushing orientation**
Factors Investigated	**Group ID**	**Sand content (% by wt of**	**Binder content (% by wt of WPA)**	**Water content (% by wt of WPA)**	**Fluid content (% by wt of**	**Natural admixture (% by wt of WPA)**	**Compacting Force(Metric ton)**	**Curing temperature / Method**	**Curing ages (days)**	**Crushing orientation**	
Curing ages	Group M5A	52	20%	75%	95%	5%	3	Ambient	**7**	As cast side	See Figure 5.8A
		52	20%	75%	95%	5%	3	Ambient	**14**	As cast side	
		52	20%	75%	95%	5%	3	Ambient	**21**	As cast side	
		52	20%	75%	95%	5%	3	Ambient	**28**	As cast side	
		52	20%	75%	95%	5%	3	Ambient	**60**	As cast side	
		52	20%	75%	95%	5%	3	Ambient	**90**	As cast side	
Water content	Group M5B	52	20%	**75%**	95%	5%	3	Ambient	28	As cast side	
		52	20%	**60%**	85%	5%	3	Ambient		As cast side	
		52	20%	**45%**	65%	5%	3	Ambient		As cast side	
		52	20%	**30%**	55%	5%	3	Ambient		As cast side	
		52	20%	**15%**	35%	5%	3	Ambient		As cast side	
Binder quantity	Group M5C	52	**20%**	75%	95%	5%	3	Ambient	28	As cast side	
		52	**40%**	55%	95%	5%	3	Ambient		As cast side	
		52	**60%**	35%	95%	5%	3	Ambient		As cast side	
		52	**80%**	15%	95%	5%	3	Ambient		As cast side	
Compacting force	Group M5D	52	20%	75%	95%	5%	**2.5**	Ambient	28	As cast side	
		52	20%	75%	95%	5%	**3.0**	Ambient		As cast side	
		52	20%	75%	95%	5%	**3.5**	Ambient		As cast side	
Curing temperature	Group M5E	52	20%	75%	95%	5%	3	**Ambient (20^{0}C)**	28	As cast side	
		52	20%	75%	95%	5%	3	**Oven(30^{0}C)**		As cast side	
Crushing orientation	Group M5F	52	20%	75%	95%	5%	3	Ambient	28	**As cast Top Face**	See Figure 5.8A
		52	20%	75%	95%	5%	3	Ambient		**As cast side Face**	See Figure 5.8B

Note: Moisture content = binder content + water content

5.2.2 Result and Discussions

The properties of the specimens produced from each group mixes contained within Series 1 and Series 2 for each of the factors investigated are summarized in Tables 5.4 and 5.5.

Table 5.4: Influence of salient parameters on strength properties of mixes in series 1

SERIES 1										
Factors Investigated	**Group ID**	**Sand content (% by wt of WPA)**	**Binder content (% by wt of WPA)**	**Water content (% by wt of WPA)**	**Compacting Force (metric ton)**	**Curing ages (days)**	**Curing Method/ temperature**	**Crushing Orientation**	**Ave. compressive strength (MPa) (n=3)**	**Standard deviation**
Curing ages	Group M1A	36	20%	75%	3	**7**	Ambient	As cast side Face	0.67	0.03
		36	20%	75%	3	**14**	Ambient	As cast side Face	0.70	0.03
		36	20%	75%	3	**21**	Ambient	As cast side Face	0.72	0.03
		36	20%	75%	3	**28**	Ambient	As cast side Face	0.79	0.04
		36	20%	75%	3	**60**	Ambient	As cast side Face	0.82	0.03
		36	20%	75%	3	**90**	Ambient	As cast side Face	0.85	0.05
Water content	Group M1B	36	20%	**75%**	3	28	Ambient	As cast side Face	0.79	0.03
		36	20%	**60%**	3		Ambient	As cast side Face	1.19	0.03
		36	20%	**45%**	3		Ambient	As cast side Face	1.33	0.05
		36	20%	**30%**	3		Ambient	As cast side Face	1.53	0.03
		36	20%	**15%**	3		Ambient	As cast side Face	2.38	0.03
Binder quantity	Group M1C	36	**20%**	75%	3	28	Ambient	As cast side Face	0.79	0.03
		36	**40%**	55%	3		Ambient	As cast side Face	0.80	0.04
		36	**60%**	35%	3		Ambient	As cast side Face	0.82	0.03
		36	**80%**	15%	3		Ambient	As cast side Face	0.91	0.05
Compacting force	Group M1D	36	20%	75%	**2.5**	28	Ambient	As cast side Face	0.57	0.03
		36	20%	75%	**3.0**		Ambient	As cast side Face	0.79	0.03
		36	20%	75%	**3.5**		Ambient	As cast side Face	0.99	0.03
Curing temperature	Group M1E	36	20%	75%	**3.0**	28	Ambient	As cast side Face	0.79	0.03
		36	20%	75%	**3.0**		Oven	As cast side Face	0.76	0.05
Crushing orientation	Group M1F	36	20%	75%	**3.0**	28	Ambient	As Cast Top Face	1.60	0.04
		36	20%	75%	**3.0**		Ambient	As Cast Side Face	0.79	0.03

Table 5.5: Influence of salient parameters on strength properties of mixes in series 2

SERIES 2										
Factors Investigated	**Group ID**	**Sand content (% by wt of WPA)**	**Binder content (% by wt of**	**Water content (% by wt of WPA)**	**Compacting Force (metric ton)**	**Curing ages (days)**	**Curing Method/ temperature**	**Crushing Orientation**	**Ave. compressive strength (MPa) (n=3)**	**Standard deviation**
Curing ages	Group M5A	52	20%	75%	3	**7**	Ambient	As cast side Face	0.71	0.03
		52	20%	75%	3	**14**	Ambient	As cast side Face	0.74	0.05
		52	20%	75%	3	**21**	Ambient	As cast side Face	0.76	0.03
		52	20%	75%	3	**28**	Ambient	As cast side Face	0.84	0.04
		52	20%	75%	3	**60**	Ambient	As cast side Face	0.85	0.04
		52	20%	75%	3	**90**	Ambient	As cast side Face	0.87	0.05
Water content	Group M5B	52	20%	**75%**	3	28	Ambient	As cast side Face	0.84	0.03
		52	20%	**60%**	3		Ambient	As cast side Face	0.96	0.03
		52	20%	**45%**	3		Ambient	As cast side Face	1.01	0.05
		52	20%	**30%**	3		Ambient	As cast side Face	1.25	0.03
		52	20%	**15%**	3		Ambient	As cast side Face	1.81	0.03
Binder quantity	Group M5C	52	**20%**	75%	3	28	Ambient	As cast side Face	0.84	0.03
		52	**40%**	55%	3		Ambient	As cast side Face	0.86	0.05
		52	**60%**	35%	3		Ambient	As cast side Face	0.89	0.03
		52	**80%**	15%	3		Ambient	As cast side Face	0.99	0.05
Compacting force	Group M5D	52	20%	75%	**2.5**	28	Ambient	As cast side Face	0.60	0.06
		52	20%	75%	**3.0**		Ambient	As cast side Face	0.84	0.03
		52	20%	75%	**3.5**		Ambient	As cast side Face	1.04	0.03
Curing temperature	Group M5E	52	20%	75%		28	**Ambient**	As cast side Face	0.84	0.03
		52	20%	75%			**Oven**	As cast side Face	0.81	0.06
Crushing orientation	Group M5F	52	20%	75%		28	Ambient	**As cast Top Face**	1.70	0.04
		52	20%	75%			Ambient	**As cast side Face**	0.84	0.07

5.2.2.1 Effect of Curing Ages on the Compressive Strength of CWLB

In order to investigate the effect of curing durations, cubic test specimens were prepared using mixes Group M1A and Group M5A. The test specimens were cured for various curing periods from 7days to 90 days. Tables 5.4 & 5.5 and Figs. 5.1 (a) & (b) show the results of these tests for specimen cured at temperature of 20^0C in ambient condition.

As presented in Fig. 5.1(a), the compressive strength of CWLB specimen increases marginally as the curing durations increases in both cases (i.e. Group M1A and Group M5A). For example CWLB specimen displayed a marginally higher compressive strength at 90 days curing age compared to that obtained at 60, 28, 21, 14 and 7 days curing durations. The observed increase is linear with a negligible 18% variation between the 28 days and the 7 days compressive strength. Considering the minor difference between the compressive strength of the specimens at different curing durations, it is clear that curing duration has little or no significant effect on the development of compressive strength of CWLB, this characteristic may be attributed to the fact that the waste additive used as binder does not exhibit any chemical reaction with other constituent materials but rather binds mechanically under the action of pressure. Also, using the 90 days strength as a reference in this case, it can be inferred that CWLB is capable of achieving about 79% of its compressive strength at 7 days curing duration. This observation is almost similar to the conventional behaviour of concrete which gains appreciable strength overtime due to the hydration process that occurs during its curing process (Akinwumi *et al.*, 2014b) though in the case of CWLB drying process is more applicable (instead of hydration process) and the strength gain over time is insignificant.

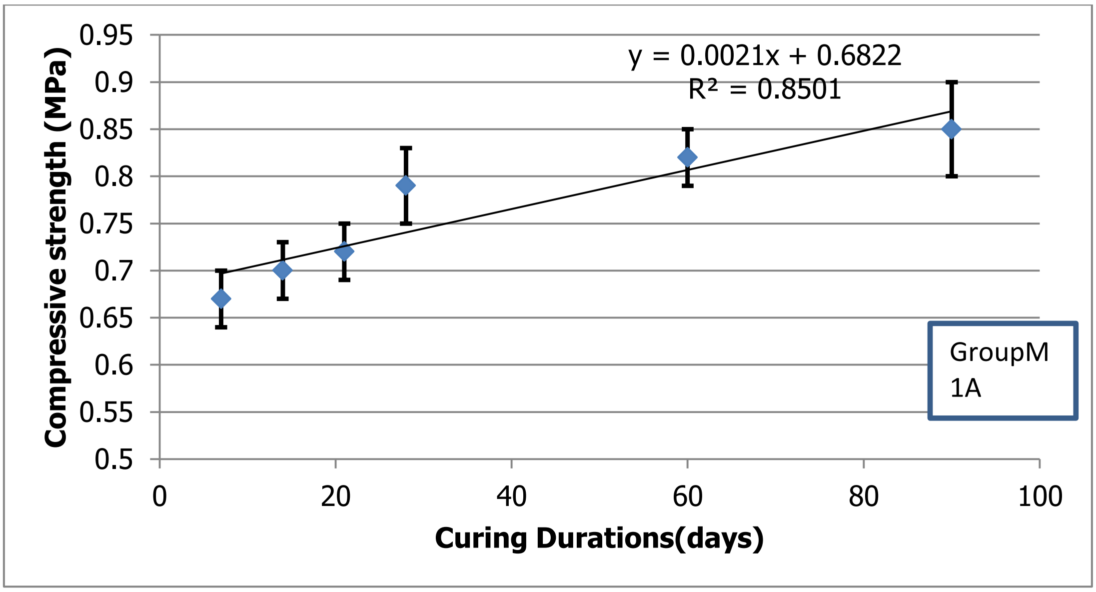


Fig 5.1a: Effect of Curing durations on compressive strength of CWLB specimen produces from mixture Group M1A

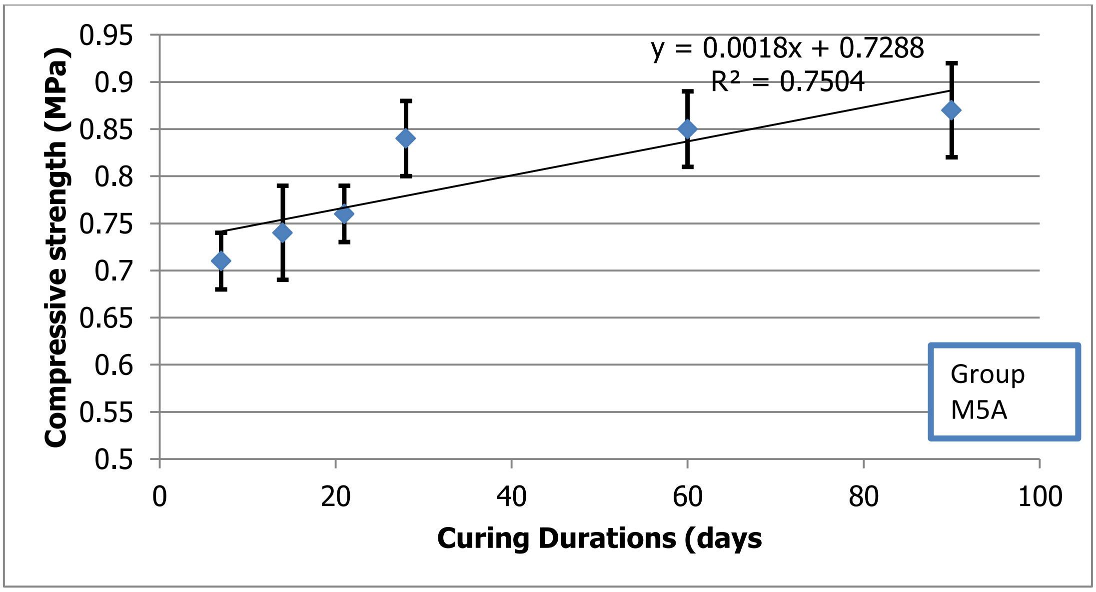


Fig 5.1(b): Effect of Curing Ages on compressive strength of CWLB specimen produces from mixture Group M5A

5.2.2.2 Effect of Water Content on the Compressive Strength of CWLB

In papercrete blocks and masonry blocks, water in the mixture chemically reacts with the cement to produce a paste that binds the aggregates. In contrast, the water in a CWLB mixture does not appear to cause any apparent chemical reaction. Instead, the incorporated water serves as a means of mixing the constituents for consistency as well as a means of conserving the binder. However, laboratory experience showed that water content in the CWLB mixture affected the properties of the mixture during mixing and moulding in the fresh state as well as in the hardened state.

In order to investigate the effect of water content on the compressive strength of the mixture, different sets of mixtures containing varying percentages of water content by weight of WPA were made from mix Group M1B and Group M5B. The details of these mixtures are given in Tables 5.2 and 5.3. The purpose of this set was to investigate the effect of water content on the compressive strengths of CWLB, while the binder contents in the mixtures were kept constant at 20% by weight of WPA. Fig. 5.2a and Fig. 5.2b show the results of these tests cured at 20 ^{0}C in ambient condition.

As presented in Figs. 5.2(a) & (b), the compressive strength of CWLB specimen increases significantly as the water content decreases in both cases (i.e. Group M1B and Group M5B). For instance, the compressive strength of CWLB specimen produced from M1 increases as the percentage of water content in the mix decreases and it decreases as the water content increases. At 15% water content, CWLB displayed an average compressive strength of 2.38 MPa while an average compressive strength of 0.79 MPa was obtained at 75% water content. This means that reducing the water content to 15% by weight of WPA resulted in

201% increase in compressive strength of CWLB when compared to that of 75% water content by weight of WPA. Also, the fitted regression line showed an R-square value of 0.94 which indicated the existence of a strong correlation between the two variables. This finding suggested that the water to binder ratio should be part of the processing parameter to be considered for optimization of CWLB mix composition. It therefore implies that CWLB's compressive strength is highly sensitive to water content unlike papercrete whose compressive strength is reported not to be affected by neither water content (Kelly Hart, (Greenhomebuilding.com) nor water to binder ratio (Yun *et al.*, 2007; Nepal and Aggarwal, 2014). It can also be noted that at 15% water content by weight of WPA, CWLB displayed a compressive strength that maximally satisfies the 1.5MPa specified by BS EN 771-4:2011 for non-loadbearing lightweight blocks.

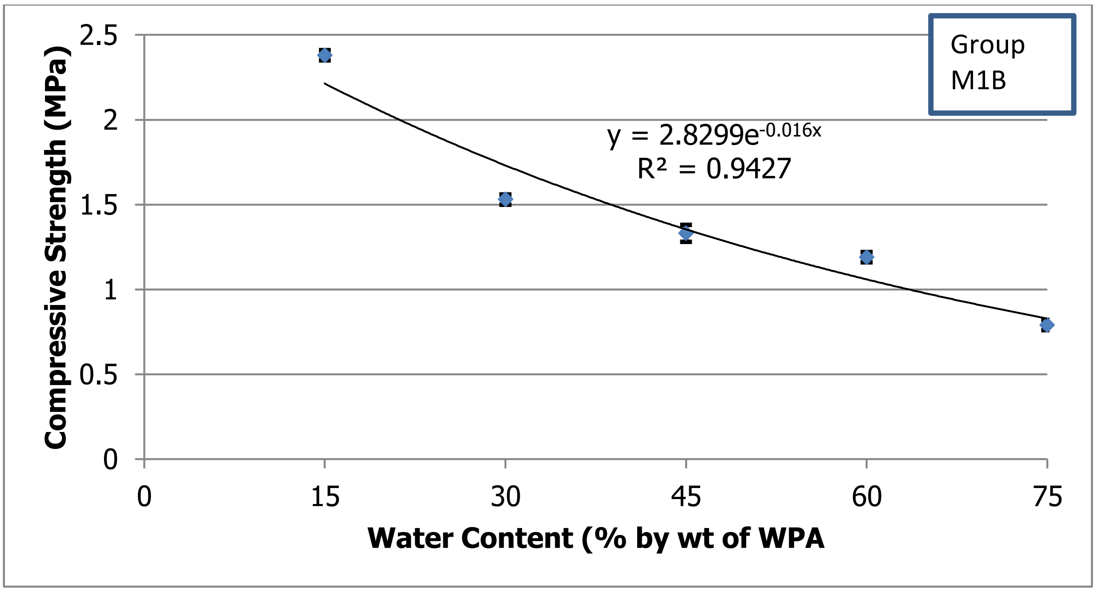


Fig. 5.2a: Effect of Water content on compressive strength of CWLB produced from Mixture Group M1B

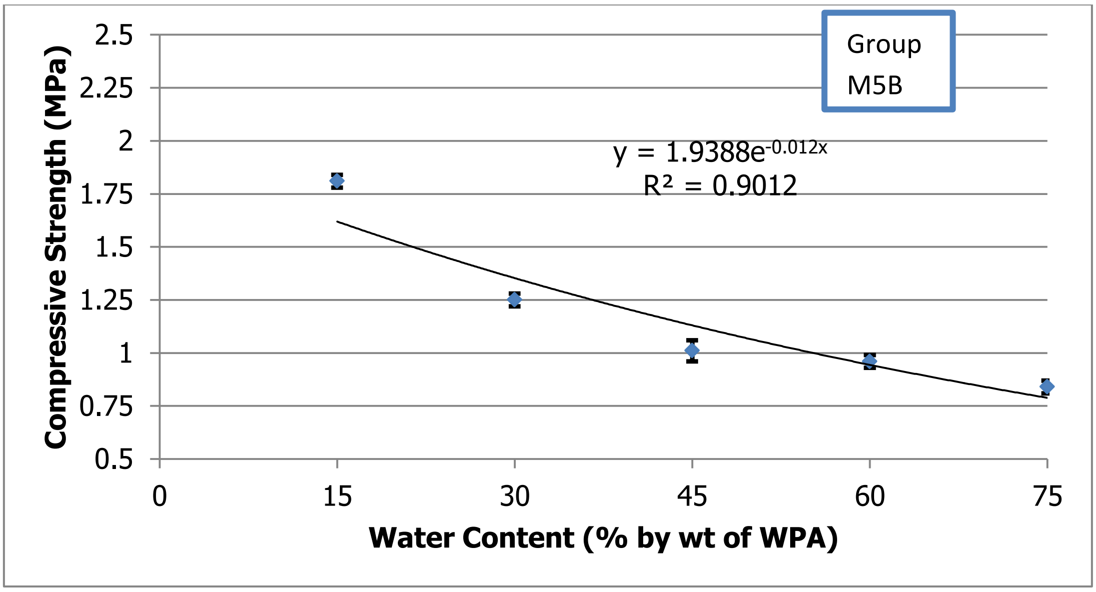


Fig 5.2b: Effect of Water content on compressive strength of CWLB specimen produces from mixture Group M5B

5.2.2.3 Effect of Binder Quantity on the Compressive Strength of CWLB

Having arrived at an optimum binder content of 20% by weight of WPA from the trial experimentation, an investigation of the effect of higher binder quantity on the compressive strength of CWLB was considered as desirable. As detailed in Tables 5.2 and 5.3 a series of mixtures were prepared to investigate the compressive strength of mix Group M1C and Group M5C at varying binder quantity ranging from 20% to 80% by wt of WPA while adjusting the water content to maintain equivalent moisture content of 95% by wt of WPA in each mixture (note: Fluid Content = water content + binder content).

As shown in Figs. 5.3a & 5.3b, the compressive strength of CWLB increases slightly as the binder content increases. A slight percentage increase of 18% was observed in the compressive strength of CWLB specimen containing 80% binder content compared to those containing 20% binder content. This implies that the increasing binder quantity beyond 20% has a minor effect on the compressive strength of CWLB. It should however be recalled that a significant strength increase ranging from 30-50% was observed for specimen containing 20% binder compared to those containing 0% binder (see Appendix 1 section Apx. 1.5.1). This means that increasing the binder content beyond 20% (by wt. of WPA) is not justified for compressive strength improvement. Therefore, keeping the binder quantity at a minimum will be highly beneficial for the purpose of sustainability and economy of production. The observed increase of CWLB's compressive strength at higher binder content is similar to the reported effect of cement on papercrete's compressive strength (Yun *et al.*, 2007) although at a lower rate.

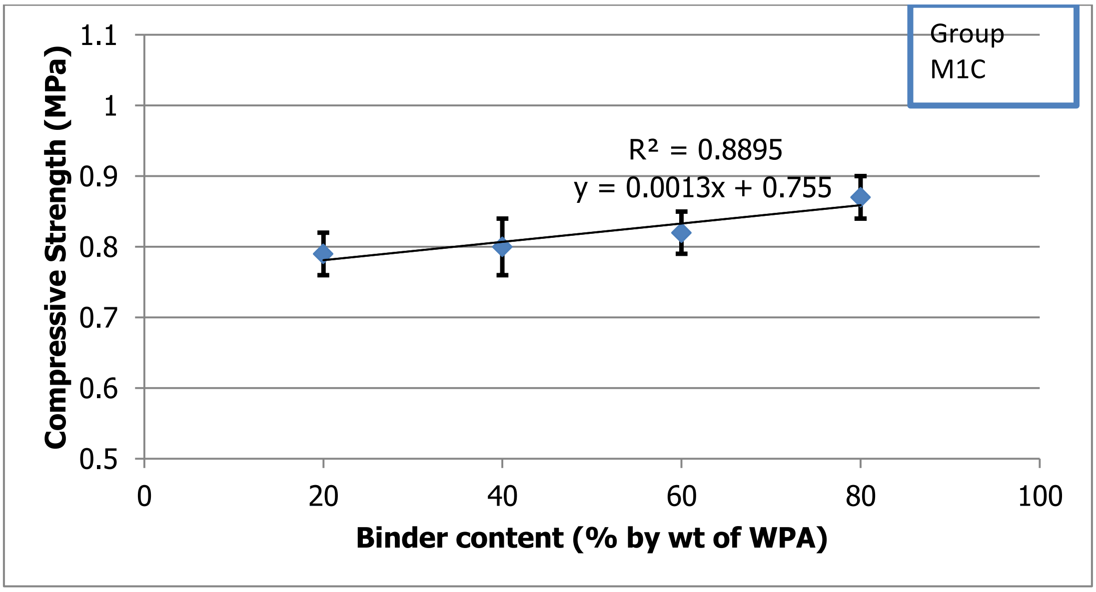


Fig. 5.3a: Influence of binder quantity on the Compressive Strength of CWLB specimen produces from mixture Group M1C

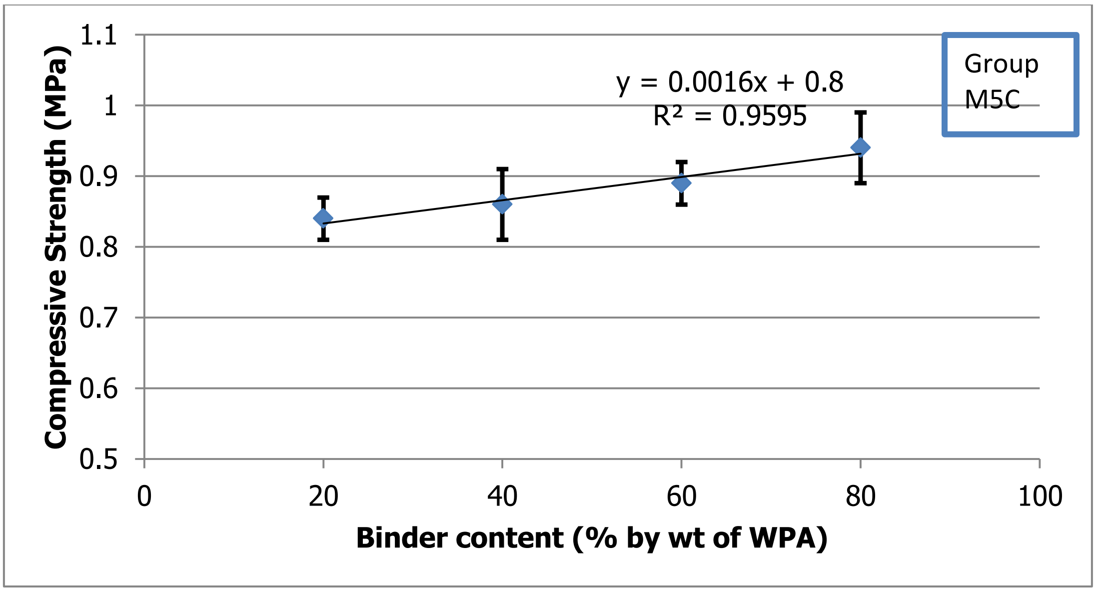


Fig. 5.3b: Influence of binder quantity on the Compressive Strength of CWLB specimen produces from mixture Group M5C

5.2.2.4 Effect of Compacting Forces on the Compressive Strength of CWLB

Blocks are produced through the application of energy to a loose mixture of constituent material (which in the case of masonry includes sand, cement, water and optional admixture and the in the case of CWLB includes WPA, sand, waste additive (i.e. waste lactose) and admixtures (i.e. stoneware clay)) place in a mold of predetermined shape and size. The energy required to form the blocks are usually applied through different methods including; hand tamping, pressing in a rigid still mold with the aid of lever or hydraulic press, slamming a hinged and weight on the exposed top of a mix and motorised vibration (Gooding and Thomas, (1995)). In masonry blocks, increase in molding pressure improves the compressive strength (Riza *et al*., 2011; Bahar *et al*., 2004) and the binder content becomes more effective at higher molding pressure compared to the lower molding pressure

In order to investigate the effect of compacting pressure on the compressive strength of the CWLB, different sets of specimens molded at varying compacting pressures of 2.5 metric ton to 3.5 metric ton (corresponding to a molding pressure of 9.8 MPa to 13.7 MPa) at an interval of 0.5 metric ton were made from mixture Group M1D and Group M5D. The details of these mixtures are given in Tables 5.2 and 5.3. The purpose of this set was to investigate the effect of molding pressure on the compressive strength of CWLB, while all other parameters remained constant except for the in-mold quantity since experience from preliminary experimentation shows that the density of CWLB blocks depends on compaction pressure. Fig. 5.4a and Figure 5.4b show the results of these tests.

In both cases, higher compacting forces significantly increased the compressive strength of CWLB. As presented in Fig. 5.4a the compressive strength of CWLB increases as the compacting forces increase. The compressive strength obtained at 3.5 metric ton was 74% higher than that obtained at 2.5 metric ton. The higher strength observed at higher compacting pressure may be an indication of pore filling effect, increase homogeneity and improved bonding that must have occurred within the microstructure of the block under the application of the pressure. According to the literature, compacted block specimens exhibit air spaces and low density at low molding pressure, while they display reduced voids, higher compaction and density at higher molding pressures (Subramania and Benny 2013). This finding indicated the need to consider the compacting force as part of the variable for optimization of CWLB to arrive at optimum processing parameters. In addition, the fitted regression line shows an R^2 value of 0.9992 which is an indication that a strong relationship exists between the compressive strength of CWLB and the applied compacting forces.

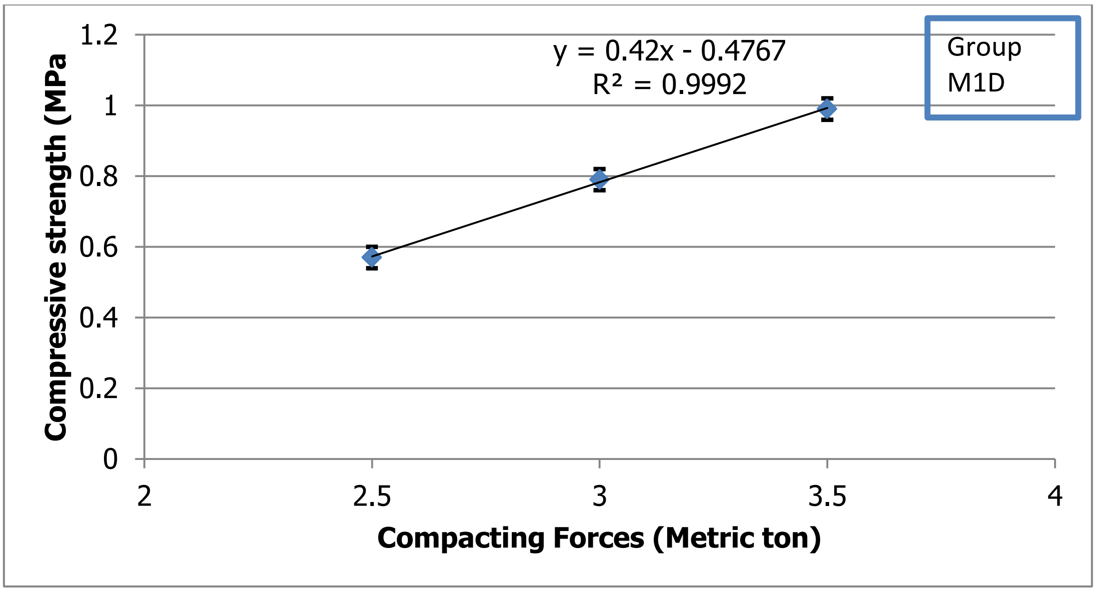


Fig. 5.4a: Effect of compacting forces on the compressive strength of CWLB specimen produces from mixture Group M1D

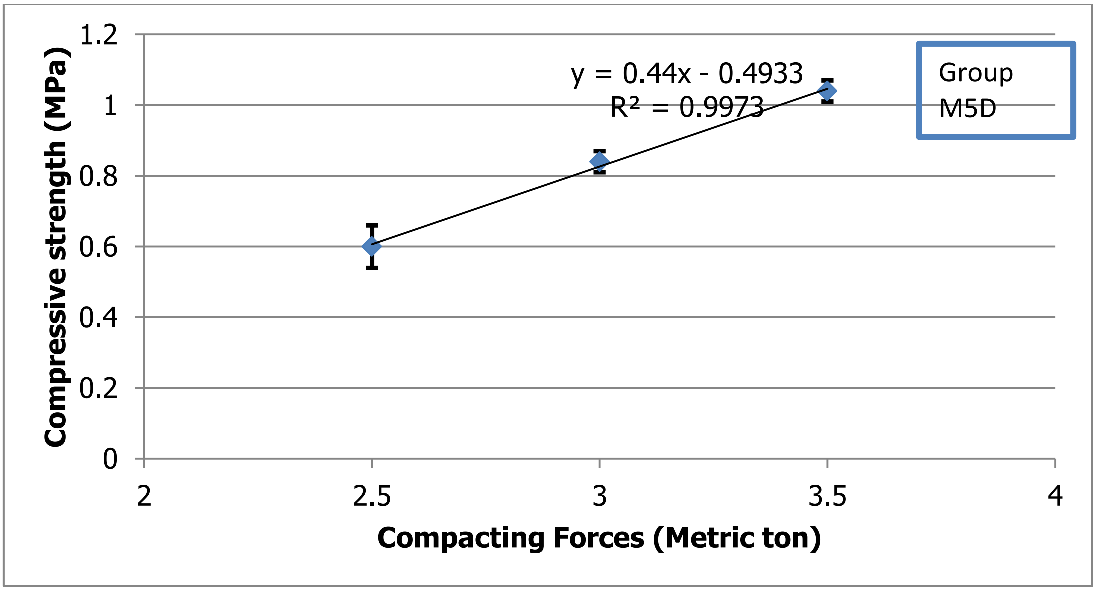


Fig. 5.4b: Effect of compacting forces on the compressive strength of CWLB specimen produces from mixture Group M5D

5.2.2.5 Effect of Curing Method/Temperature on the Compressive Strength of CWLB

Figs. 5.5a and 5.5b shows the effect of curing temperature on the compressive strength of CWLB specimen produced from mixtures Group M1E and Group M5E after dry curing at two different temperature of 20^0C and 30^0C corresponding to ambient and oven curing condition respectively. All other test variables were held constant. The ambient cured specimens were kept in room condition at 20 ^{o}C temperature until the 28 days testing age, while the oven cured specimen were subjected to curing in the oven at 30 ^{0}C for 28 days and were taken out to cool down to room temperature before testing. The oven cured temperature of 30 ^{o}C was adopted to replicate the average temperature condition that the specimen may be subjected to in a hot/warm temperate region. Investigating this parameter is expected to help in determining the suitability of using the CWLB in the hot/warm environments.

As shown in Fig. 5.5a lower curing temperature at ambient condition resulted in marginally higher compressive strength, although curing at a higher temperature of 30 ^{0}C inside oven did not decrease the compressive strength substantially. For both mixture M1 and M5, the observed percentage increase was 4% for ambient cured specimen compared to the oven cured specimen. Considering the negligible variation, it is clear that curing at higher or lower temperature produces little or no significant effect on the development of compressive strength of CWLB. This indicates the possibility of utilizing the CWLB block at both hot and cold temperate regions.

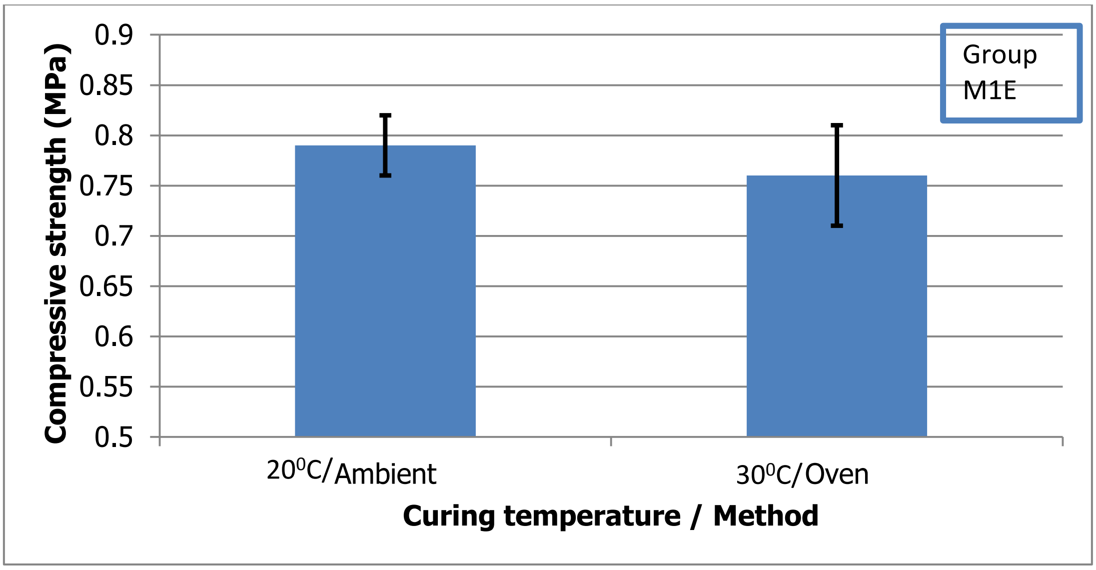


Fig. 5.5a: Effect of curing method/Temperature on compressive strength of CWLB specimen produces from mixture Group M1E at 28days curing duration

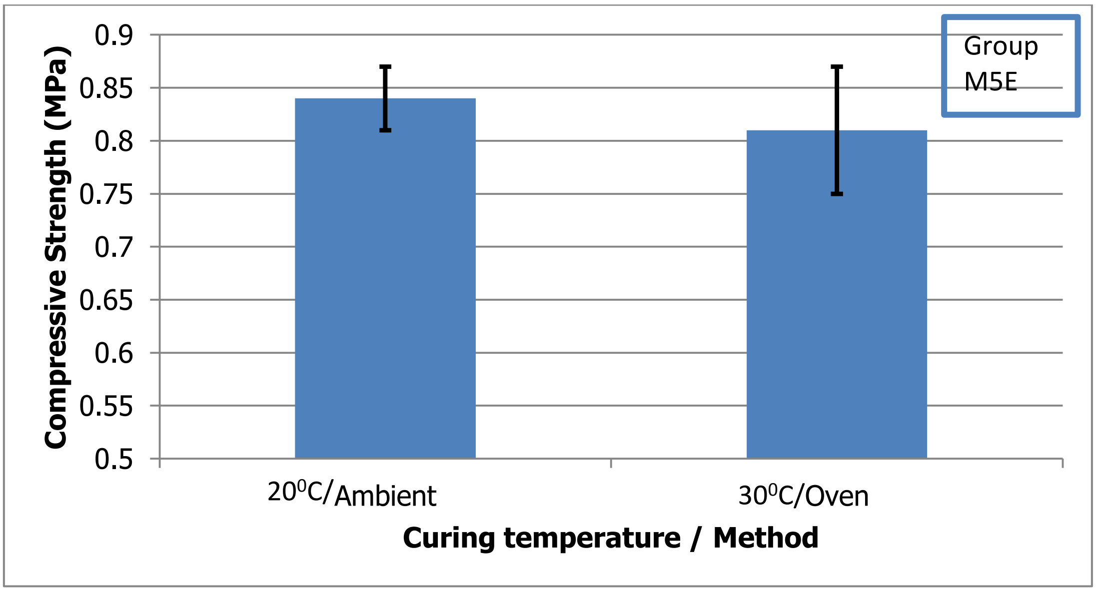


Fig. 5.5b: Effect of curing method/Temperature on compressive strength of CWLB specimen produces from mixture Group M5E at 28days curing duration

5.2.2.6 Effect of Crushing Orientation on the Compressive Strength of CWLB

In masonry construction, loading orientation of block units affects the compressive strength of masonry (Baiden and Asante, 2004). Also, the compaction/molding orientation employed during production has been reported to affect the compressive strength of the resulting masonry units (Baiden and Asante, 2004). Blocks molded in the vertical orientation using a motorized vibration method usually exhibits higher compressive strength compared to those molded in the horizontal orientation.

The compressive strength displayed by the CWLB specimen subjected to crushing on the as-cast side-face (SF) and the as-cast top-face (TF) are presented in Figs. 5.6a and 5.6b for specimen produced from mixture Group M1F and Group M5F respectively. In both cases, the specimen crushed on the top-face displayed approximately 101% higher compressive strength compared to specimen that was crushed on the as-cast side-face. A ductile mode of failure was also observed in specimen crushed on the top-face while a brittle mode of failure was observed in specimen crushed on side-face.

The physical observation of the specimen cross section (as illustrated in Fig. 5.7) shows that, similar to the reported mechanism of densification of biomass in which granular particles tend to rearrange themselves under the application of compaction forces to fill up void or air spaces (Kaliyan and Morey 2009a & b), the wastepaper fibres present in CWLB mixture rearranged themselves in a direction perpendicular to direction of the applied moulding pressure during the process of compaction under the hydraulic press (see Figs. 5.8A and 5.8B). This means that when CWLB specimen is loaded on the top-face, the applied crushing load acted in the direction perpendicular to its fibre orientation whereas when it is loaded from the side face, the applied crushing load acted in the direction parallel to its fibre orientation.

Related Studies have shown that brittle failure mechanism of densified granular biomass in a particular fibre direction may indicate the presence of weak boundary layers between adjacent fibres along such direction (Stelte *et al.*, 2011). The fact that higher strength was recorded on the top face loading orientation implies that the bonding forces (e.g. mechanical interlocking or adhesion and cohesion (Stelte *et al.*, 2012)) that exist between the fibres are stronger to resist compressive load applied perpendicular to their orientation rather than those applied parallel to their orientation. This indicates that the CWLB block specimen are tougher in the direction perpendicular to their fibre orientation and are weaker in the direction parallel to their fibre orientation. A comparison of this characteristic with wood indicates that the CWLB exhibit properties different from wood in terms of loading orientation given the fact that wood is stronger in the direction of orientation of its fibre and are weaker in the direction perpendicular to its fibre orientation (Thelanderson and Larsen, 2003).

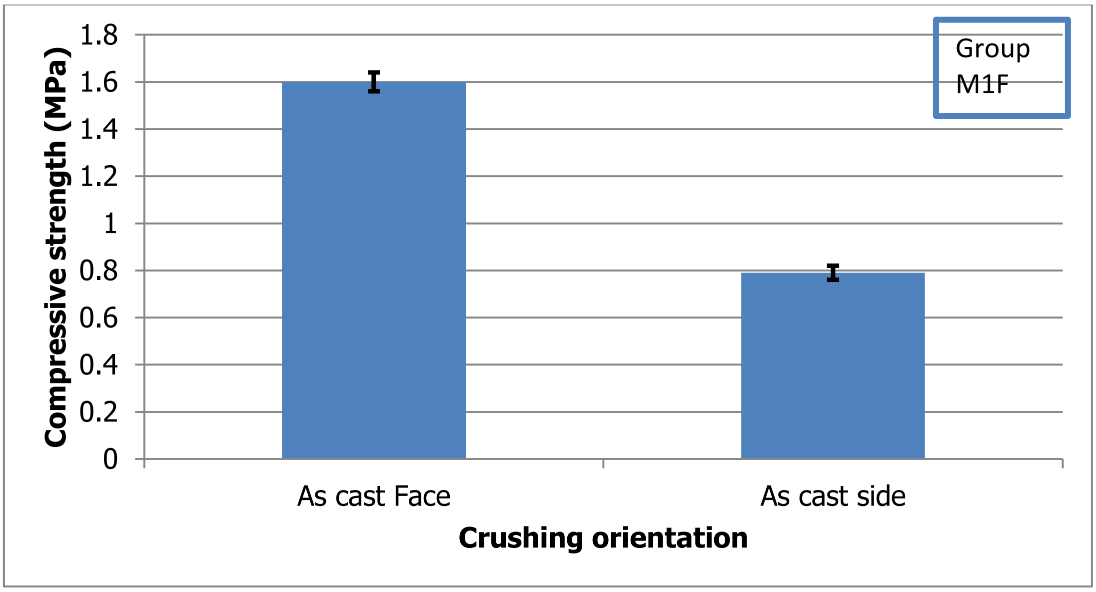


Fig. 5.6a: Effect of crushing orientation on compressive strength of CWLB specimen produces from mixture Group M1F

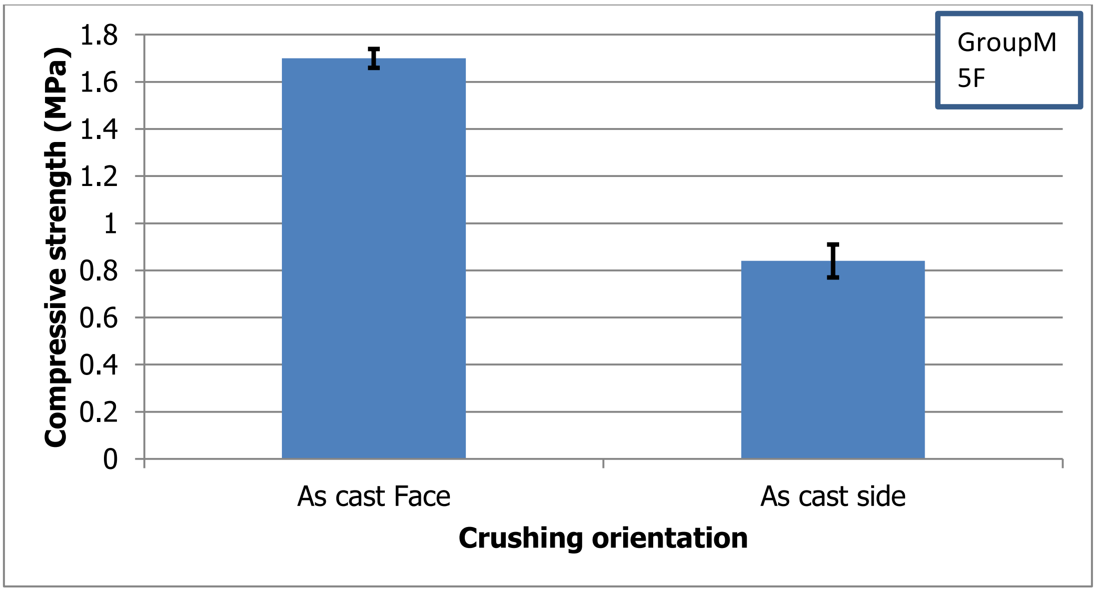


Fig. 5.6b: Effect of crushing orientation on compressive strength of CWLB specimen produces from mixture Group M5F

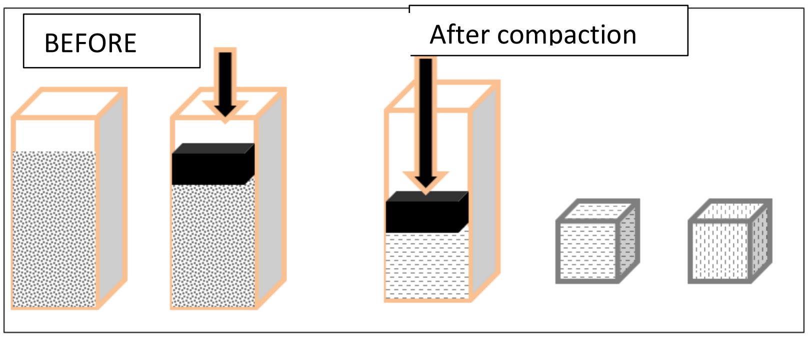


Fig. 5.7: Cross section of fibre arrangement before and after compaction

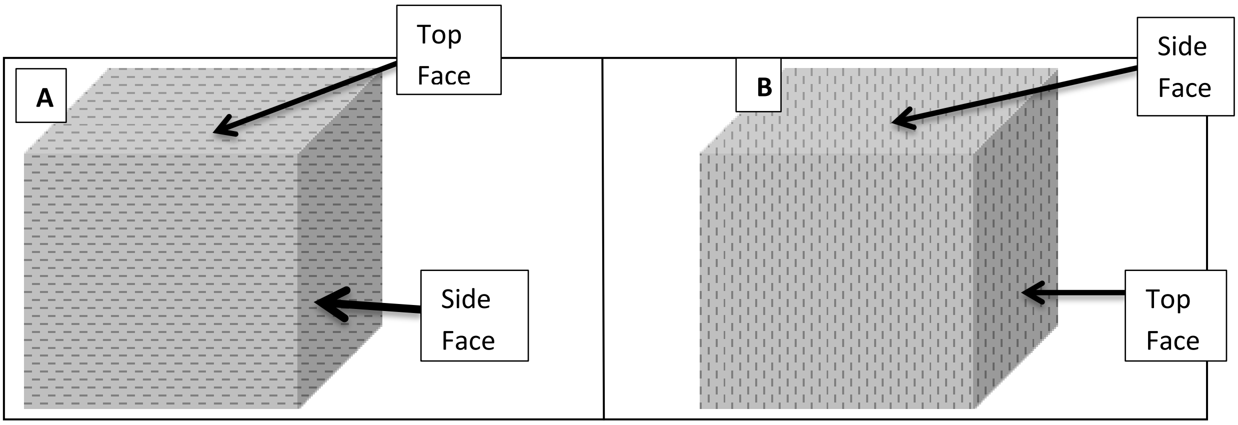


Fig. 5.8: (A) Illustration of CWLB specimen AS CAST TOP FACE orientation (illustrating the orientation of compressed WPA) (B) CWLB specimen AS CAST SIDE FACE orientation (illustrating orientation of compressed WPA)

5.2.3 Inferences from salient parameters studied

The findings from the study presented in this section led to the following conclusions:

- The compressive strength of CWLB at 28days curing age is 16% higher than those cured at 17days curing age..
- The compressive strength of specimen containing 15% water content was 219% higher than those containing 75% water content.

- The compressive strength of specimen containing 80% binder content was 18% higher than those containing 20% binder content.
- The CWLB specimen loaded and crushed on the top-face displayed approximately 101% higher compressive strength compared to those loaded and crushed on the as cast side.
- The compressive strength of CWLB increases as the compacting force used for molding increases.

The outcome of the experimentation generally suggests the need to consider the water to binder ratio along with the compacting forces as processing parameters for optimization of CWLB mix composition.

5.3 OPTIMIZATION OF MIX COMPOSITION AND COMPRESSIVE STRENGTH OF CEMENT-LESS WASTEPAPER LIGHTWEIGHT BLOCK (CWLB)

5.3.1 Introduction

Based on the findings from the study of factor effects the processing parameters which includes; Water content, binder content, and compacting force were found to have the most crucial effect on CWLB's compressive strength. Therefore, for the purpose of maximizing the compressive strength of CWLB to satisfy the strength requirements for non-structural/non-load bearing blocks, this optimization study was conducted to determine the optimum mixture composition for CWLB. This aim was achieved by employing the Taguchi statistical optimization technique in conjunction with laboratory experimentation.

5.3.2 Taguchi Method

The Taguchi method is a statistical optimization process technique developed by Genichi Taguchi during the 1950s (Roy, 1990). It is a Design of Experiment (DOE) (Montgomery, 2013) approach that is grounded on quality philosophy which seeks to develop product and processes that are robust to environmental factors and other sources of variation. Robustness can be described as the extent of the product or processes capabilities to perform efficiently and consistently with minimal effect from the uncontrollable noise factors due to operation or manufacturing (Montgometry, 2013).

The use of Taguchi approach in product development offers design engineer a proficient and an organised means of determining a near optimum design parameters for quality performance. The concept of Signal-to-noise-ratio encompassed within the Taguchi method enables the measurement of the variability of performance response relative to the desired value under different noise conditions. Taguchi method recognises that in product development, some factors that cause variability can be controlled while there are also factors that are uncontrollable. The uncontrollable factors are known as noise factors. The identification of controllable factors is important in Taguchi DOE, because in the course of experimentation, noise factors are controlled to force variability to occur thereby leading to the determination of optimal control factors settings that make the processor product robust or resistant to variation form the noise factors. The noise factors are regarded as the cause of variability in performance as well as product failure. The S/N ratio helps to evaluate the stability of performance of an output characteristic (Nurudin and Bayuaji, 2009).

The previously performed series of trial experimentation and salient parameter studies have already addressed the steps 1-4 of the procedure for Taguchi design methodology (Fig. 5.9). This study therefore employs the steps 5 to 10 of the Taguchi method to determine the best combination of processing parameters/control factors required to obtain the optimum mixture composition for CWLB with maximal compressive strength. The compressive strength of the block was solely studied as the quality response in this optimization process because of its intrinsic importance in structural design.

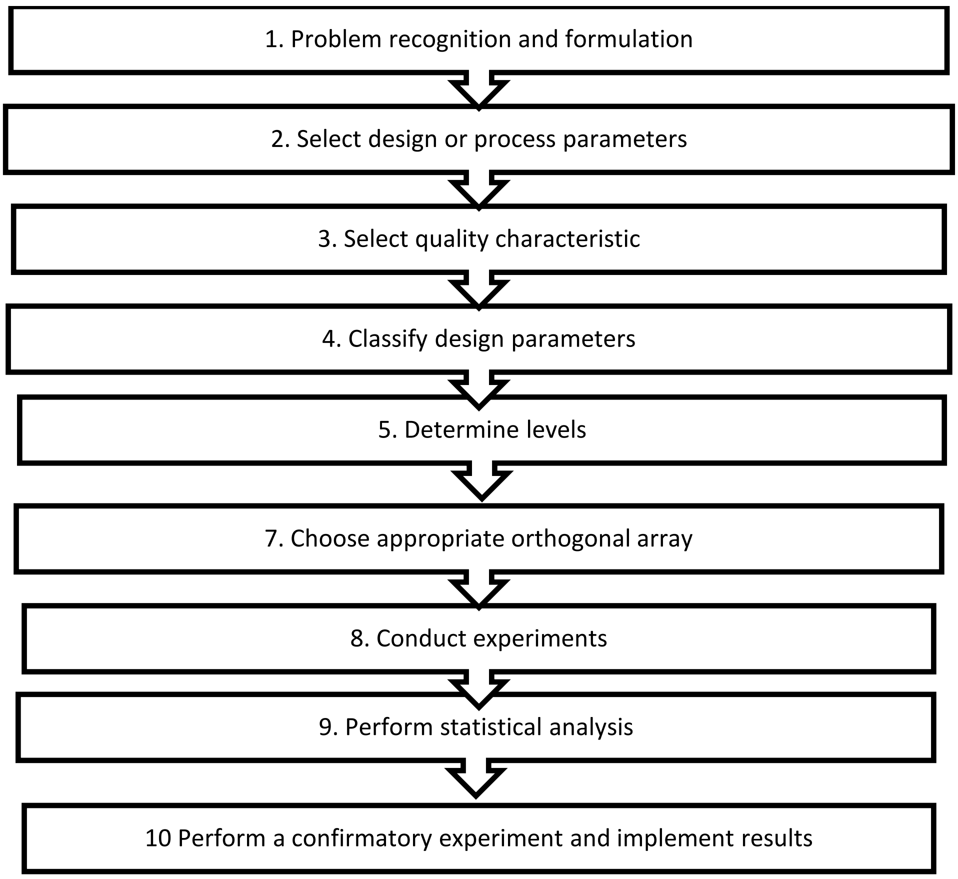


Fig 5.9: Procedure for Taguchi design methodology (Source: Adapted from Nuruddin and Bayuaji, 2009).

5.3.3 Experimental Procedure

In this study, CWLB was produced from constituent materials which include; wastepaper aggregate (WPA), sand, waste additives (binder), natural admixture

(Clay) and water. Given the variation in the physical properties of the constituent materials, batching was carried out by weight in order to achieve accurate proportioning of materials for the CWLB mixes. Several mixes were prepared from varied combinations of WPA/Sand ratios, WPA/binder ratios, and water/binder ratios. CWLB specimens of sizes 50mmx50mm x50mm were molded using a 10ton manual hydraulic press containing a pre-installed pressure gauge (see Fig 4.4). The experiment was conducted with three controllable three-level processing parameters namely; WPA/Sand ratios, water/binder ratios and compacting forces. (It should be noted here that the 3 levels of WPA/Sand ratios (i.e. 2.08, 2.27, and 2.5) explored are equivalent to 40%, 44% and 48% sand content by weight of WPA respectively. It was represented in this format at this stage to simplify the Taguchi optimization process). Other processing parameters which include; WPA particle size (passing 3.35 mm BS sieve), specimen curing time (28 days), mixing time (27 min), admixture quantity (5% by weight of WPA), were kept constant. The selected processing parameters and their levels are shown in Table 5.6.

Table 5.6: CWLB processing parameters and levels

Designations	**Control Factors**	**Units**	**Level 1**	**Level 2**	**Level 3**
A	WPA/sand ratio	-	2.08	2.27	2.5
B	Water/binder ratio	-	0.75	2.25	3.75
C	Compacting force	Metric ton	3	3.25	3.5

With three factors, each with three levels, the full factorial design would require $3^3 = 27$ possible combinations of trials. Carrying out a large number of experiments for all the combinations will amount to excessive resources and time consumption. The Taguchi method designs an orthogonal array (OA) to simplify the large number of experiments, and allocates them into a smaller number of trials to run the experiment. Orthogonal array is an arrangement of numbers in columns and rows in a manner that each column represents a factor while the rows stand for levels of the factors (Davies *et al.*, 2015). Only three processing parameters, each with three levels, were considered in this study, nine trials of CWLB specimen with varied compositions were produced using the L_9 (3^3) OA, as presented in Tables 5.7a and 5.7b.

Table 5.7a: Table of Taguchi L9 (33) Orthogonal Array (Source: Zarmai et al., 2015)

Experiment Number	**Factors and level**			**Parameter setting**
	A (WPA/Sand ratio)	B (Water/Binder ratio)	C (Compacting Force)	
1	1	1	1	A1B1C1
2	1	2	2	A1B2C2
3	1	3	3	A1B3C3
4	2	1	2	A2B1C2
5	2	2	3	A2B2C3
6	2	3	1	A2B3C1
7	3	1	3	A3B1C3
8	3	2	1	A3B2C1
9	3	3	2	A3B3C2

The 50mm x 50mm x 50mm CWLB specimen produced from the experimental run in Table 5.7b were subjected to curing in ambient laboratory air for 28 days. The density and the dimensional deviation of the specimen at 28 days curing age were determined in accordance with BS EN 772-13(2011) and BS EN772-16(2011) specifications respectively. Compressive strength test was conducted on the specimen in accordance with BS EN 772-1(2011) specification. The result of compressive strength obtained was analysed by adopting the (the bigger the better) signal-to-noise (S/N) ratio and by analysis of variance (ANOVA) in order to determine the optimal processing parameter required to produce CWLB with satisfactory compressive strength and to establish the impacts of each processing parameter on the compressive strength of CWLB.

Table 5.7b: Table of Taguchi Orthogonal Array L9 (33) showing details of CWLB parameter combinations

Experiment Number	**Factors and level**			**Parameter setting**
	A (WPA/Sand ratio)	B (Water/Binder ratio)	C (Compacting Force)	
1	1(2.08)	1(0.75)	1(3)	A1B1C1
2	1(2.08)	2(2.25)	2(3.25)	A1B2C2
3	1(2.08)	3(3.75)	3(3.5)	A1B3C3
4	2(2.27)	1(0.75)	2(3.25)	A2B1C2
5	2(2.27)	2(2.25)	3(3.5)	A2B2C3
6	2(2.27)	3(3.75)	1(3)	A2B3C1
7	3(2.5)	1(0.75)	3(3.5)	A3B1C3
8	3(2.5)	2(2.25)	1(3)	A3B2C1
9	3(2.5)	3(3.75)	2(3.25)	A3B3C2

5.3.4 Analysis Method

In analysing the results, the (S/N) ratio introduced by Taguchi for determining product quality characteristics was adopted. In Taguchi method, a high S/N ratio implies that the signal is much higher than the random effect of the noise factors. The part or process operation consistent with the highest S/N ratios always yields optimal quality characteristics with minimum variance. Also, quality characteristics in the Taguchi method can be categorized into; 'the smaller the better' (indicating minimization), 'the nominal the better' (indicating Nominalization) and 'the bigger the better' (indicating Maximization) (Nuruddin and Bayuaji, 2009).

5.3.4.1 Determination of S/N ratio for the response characteristic

In the study of the mechanical properties especially the compressive strength of blocks, higher strength is usually desired. Therefore, since the focus of this study was to maximize the compressive strength of CWLB, the S/N ratio which correspond to 'the bigger the better' quality characteristic was utilized in the analysis, and it was calculated using Eqn. (5.1) (Nuruddin and Bayuaji, 2009):

$$S/N_L = -10log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \quad \text{.............} \quad \text{.................. Eqn 5.1}$$

Where:

y_i is the value of the compressive strength for the ith trials,

n is the numbers of samples, and

S/N_L is the symbol representing 'the bigger the better' signal-to-noise-ratio.

In this analysis, the level of the factor with the larger S/N ratio denotes that this level can result in a larger compressive strength. By selecting the level with a larger S/N ratio for each factor, the estimation of the set of optimal levels of the processing parameters for CWLB was actualized. A confirmation test/selection of optimum parameter setting according to the identified optimal factor levels was carried out as applicable. The experimental results, as well as the computed S/N_L ratios for each parameter settings are presented in Table 5.8.

5.3.4.2 Determination of mean of S/N_L ratio, the main effect of control factors and the rank of effect.

The average effect response for S/N_L ratio of each factor was investigated to determine the contributions of WAP/Sand ratio, Water/binder ratio, and Compacting force to the magnitude of the compressive strength. Minitab 17 statistical software was used to carry out analysis of variance (ANOVA) on the experimental results and the corresponding computed S/N ratio and also used to obtain the main effect plot for S/N_L ratio. The mean of S/N_L ratio ($\bar{j}_i$) (which represented the factor average effect at each level) was obtained by applying the expression for determining average of S/N_L ratio for each factor (Zarmai *et al*., 2015) as shown in Eqn. 5.2 . The effect of each factor (E_j) (which is simply the observed range of S/N ratio at different factor levels) was obtained by using the expression (Zarmai *et al.*, 2015) shown in Eqn. (5.3). The rank was estimated based on the magnitude of the effect of each factor

$\bar{j}_i = \frac{1}{n}\sum_{j_i=1}^{n} j_i \,|_{\forall j,i}$ ....Eqn. 5.2

Where:

j represents any of the factors A, B or C (at any instance)

i stands for any of the levels 1, 2 or 3 (at any instance)

$\bar{j}_i$ is the mean of S/N ratio

n is the number of levels in the experiment

The sign $|_{\forall j,i}$ signifies that Eqn.(5.2) was evaluated at j and i values.

$E_j = F_{jmax} - F_{jmin}|_{\forall i}$ ....Eqn 5.3

Where:

E_j is the effect of factor j

F_{jmax} and F_{jmin} are maximum and minimum value of factor j respectively. The sign $|_{\forall i}$ indicates that Eqn. 5.3 was evaluated across the level.

5.3.5 Results and Discussions

5.3.5.1 Compressive strength test result for each CWLB experimental run

The plot of compressive strength test result for each experimental run is presented in Fig. 5.10. It was observed that experiment number 7 displayed the highest compressive strength compared to all other experimental runs.

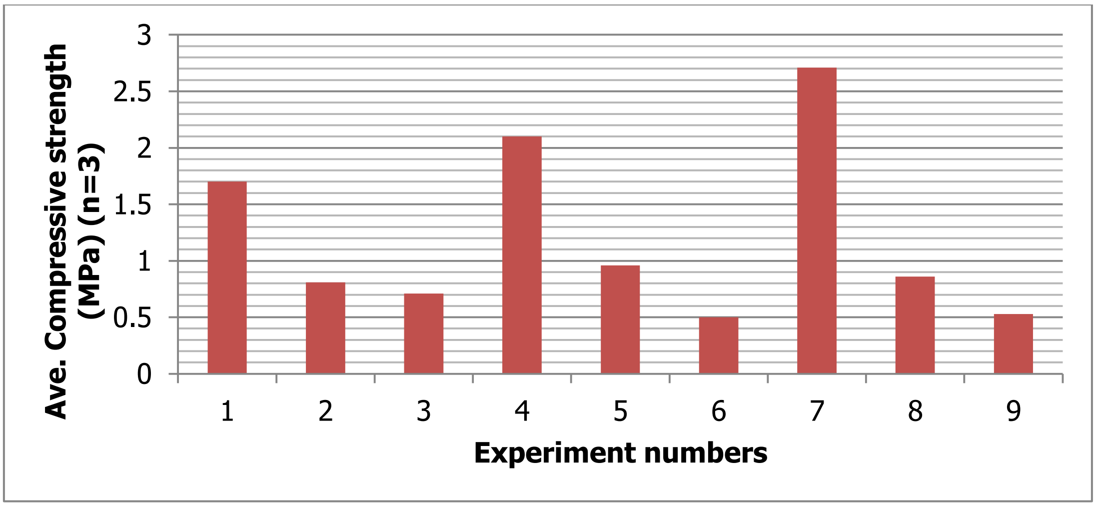


Fig. 5.10: Plot of compressive strength test result for each CWLB experimental run

Also, the CWLB produced from experiment number 6 displayed the lowest compressive strength compared to others. This indicates that parameter combination in experiment number 6 is the worst parameter setting compared to others.

5.3.5.2 Main effect of processing parameter/control factors

In this study, the compressive strength result of CWLB produced from each experimental run was statistically analysed using S/N ratio which corresponds to the "bigger the better" quality characteristics and was computed based on Eqn. 5.1, since the higher compressive strength is desired. The computed S/N ratios for each parameter combinations are presented in Table 5.8.

Table 5.8: Experimental Results and Computed S/N_L ratio

Experiment Number	Factors and level			Response	S/N_L ratio
	A (WPA/Sand ratio)	B (Water/Binder ratio)	C (Compacting Force)	Ave. Compressive strength (MPa) (at 28 days) (n=3)	
1	1	1	1	1.7	4.609
2	1	2	2	0.81	-1.830
3	1	3	3	0.71	-2.975
4	2	1	2	2.10	6.444
5	2	2	3	0.96	-0.356
6	2	3	1	0.50	-6.021
7	3	1	3	2.71	8.659
8	3	2	1	0.86	-1.310
9	3	3	2	0.53	-5.514

Fig. 5.11 present the graph of main effect plot for S/N ratio which was plotted to find the optimum levels of WPA/Sand ratio, Water/binder ratio and the compacting force required to produce CWLB with maximal compressive strength. It was found that an increment in WPA/sand ratio lead to an increase in compressive strength of the block, while a decrease in WPA/Sand ratio resulted in a decrease in compressive strength.

However, a slight effect variation was observed within the range investigated. Low water /binder ratio resulted in higher compressive strength while high water/binder ratio leads to lower compressive strength and the effect variation was significant within the range tested. Also, the compressive strength of CWLB increases with increasing compacting force and decreases at lower compacting forces.

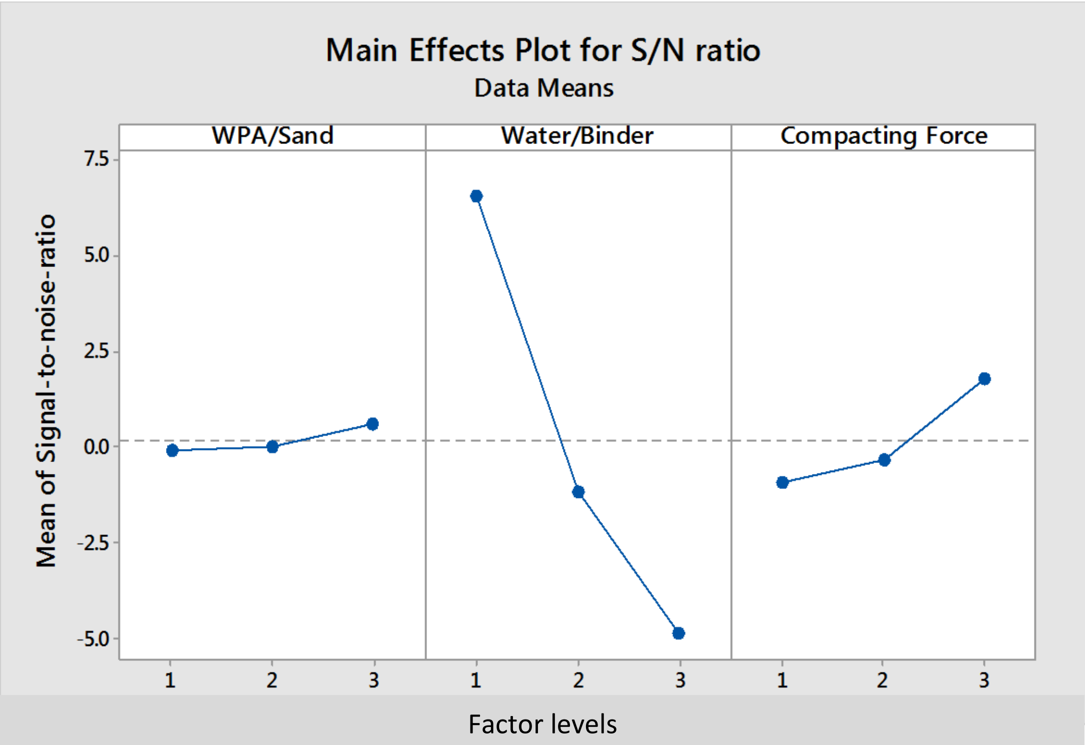


Fig. 5.11: Main effect plot for WPA/ sand ratio, Water/Binder ratio, and Compacting force.

5.3.5.3 Optimum Processing Parameters/Mixture Composition of CWLB

Judging from both Fig. 5.11 and the data presented in Table 5.9, the most significant processing parameters for CWLB is factor B (Water/Binder ratio) as it displayed the largest effect and ranked 1st. Factor A (WPA/Sand ratio) is the least significant as it exhibited the least effect, hence ranked 3rd. Factor C (Compacting Force) has the second largest effect as it ranked 2nd. Furthermore from Table 5.9, the optimal parameter setting based on maximum values was deduced to be A3B1C3 which revealed that the CWLB should be produced from a combination of 2.5 WPA/Sand ratio, 0.75 Water/Binder ratio, and 3.5 Metric ton Compacting force. This optimal parameter setting is equivalent to a mix ratio of 1:0.4:0.2 of WPA, Sand, and Binder ratio. It is also equivalent to 62.5% WPA, 25% Sand, and 12.5% binder when estimated based on aggregate and binder only (i.e. excluding water content and natural admixture).

Table 5.9: Mean of S/N Response, Effects of Factors and Rank of Effects

Description		Factor and level		
		A	B	C
$\bar{j}_i$	Level 1	-0.06	6.57	-0.91
	Level 2	0.02	-0.3	-0.3
	Level 3	0.61	-4.84	1.78
Ej	Effect	0.67	11.41	2.69
Rank of effect	Rank	3	1	2

5.3.5.4 Confirmation test and review of optimal CWLB properties

Incidentally, the identified optimal parameter setting of CWLB coincided with the parameter setting of experiment number 7 (see Table 5.8 and Table 5.10).

Therefore, the result of compressive strength for experiment number 7 was compared with the result obtained from the worst parameter setting (i.e. experiment number 6). From Table 5.10, it was established that the optimum parameter setting increases the compressive strength of CWLB by 442% compared to that of the worst parameter setting. Likewise from Table 6.10, the optimal CWLB exhibited a compressive strength of 2.71 MPa, a density of 901.5 kg/m^3 and a satisfactory dimensional deviation of +0.5mm, +0.5mm and -1.5mm on the length, width, and height respectively.

Table 5.10: Confirmation test, Properties and Optimal parameter combination for CWLB

CWLB Compositions	**Factor and level**			**Ave. Compressive strength (n=3) (MPa)**	**S/N ratio**
	A	B	C		
Worst CWLB composition	1	3	1	0.50	-5.352
Optimal CWLB composition	3	1	3	2.71	8.659
Percentage increase in compressive strength (between worst and optimal CWLB composition)				442%	-

Parameter Combination and Properties of Optimum mix composition of CWLB					
Optimal parameter combination			Properties		
WPA/Sand ratio	Water/Binder ratio	Compacting force (Metric ton)	Compressive strength (MPa)	Density (kg/m^3)	Dimensional deviation.
2.5	0.75	3.5	2.71	901.5	Satisfactory

5.3.5.5 Comparism of the compressive strength of optimal CWLB with that of optimised initial efficient trial mix composition from exploratory study

Having observed that the 2.5 optimum WPA/Sand ratio obtained from optimization study coincided with the WPA/sand ratio for trial mix M2 (see Table 5.1), it was deemed appropriate to incorporate the optimum Water/binder ratio (0.75) and the optimum compacting force (3.5 metric ton) into the initially selected trial mixes M1, M3, M4 and M5 in order to further validate the optimum processing parameter obtained from optimization study as well as confirm further the validity of the optimum mix composition obtained from the Taguchi approach. The specimen produced from the resulting optimized mixes (designated as OPT-M1, OPT-M3 OPT-M4 OPT-M5 (Table 5.11)) were subjected to compressive strength test at 28 days curing age.

Table 5.11: Optimised version of processing parameter combination for the Initial efficient trial mix composition

Optimised initial Trial mixes	WPA/Sand ratio	Water/Binder ratio	Compacting force (metric ton)
OPT-M1	2.78	0.75	3.5
OPT-M2 (Optimal CWLB)	**2.50**		
OPT-M3	2.27		
OPT-M4	2.08		
OPT-M5	1.92		

As presented in Table 5.12, the result showed that the optimal mix composition (M2) displayed the highest average compressive strength compared to other optimised trial mixes including M1, M3, M4, and M5. The trend shows that beyond the Optimal mix composition (i.e. 40% sand content by weightt of WPA) the compressive strength of CWLB decreases marginally as the sand content increases and increases otherwise. For example, the percentage decrease in strength is 6%, 8% and 11% for mixes OPTM3 OPTM4 and OPTM5 which contained 44%, 48% and 52% sand content (by weight of WPA) respectively when compared with the optimum mix composition(M2) which contained 40% sand content by weight of WPA. Also, below the 40% optimum sand content compressive strength dropped from 2.71 MPa to 2.59 MPa. These findings further validates the optimum mix composition obtained from the optimization study.

Table 5.12: Compressive strength of optimized selected trial mixes compared with optimal CWLB

Optimized mixes	**Ave. Compressive strength (n=3) (MPa)**
OPT-M1	2.59
OPT-M2 (Optimal CWLB)	**2.71**
OPT-M3	2.56
OPT-M4	2.49
OPT-M5	2.39

Similarly, it was noted that each of the mixes tested displayed satisfactory compressive strength. As shown in Table 5.13 and Fig. 5.12, the optimized mixes including OPTM1, Optimal CWLB, OPT-M3, OPT-M4, OPT-M5 comparatively displayed 287%, 442%, 412%, 379%, 373% higher compressive strength than the initial trial mixes M1, M2, M3, M4, and M5 respectively. This clearly validates the optimum processing parameters arrived at and the corresponding maximization of compressive strength of CWLB.

Table 5.13: Comparison of the compressive strength of trial mixes and optimized mixes

Trial mixes		Optimized mixes		Percentage increase
Trial Mix designation	**Compressive strength (MPa) (at 28 days) (n=3)**	**Optimized Mix Designation**	**Compressive strength (n=3) (MPa) (at 28 days)**	
M1	0.67	OPT-M1	2.59	287%
M2	0.50	**OPT-M2 (Optimal CWLB)**	**2.71**	**442%**
M3	0.50	OPT-M3	2.56	412%
M4	0.52	OPT-M4	2.49	379%
M5	0.64	OPT-M5	2.39	373%

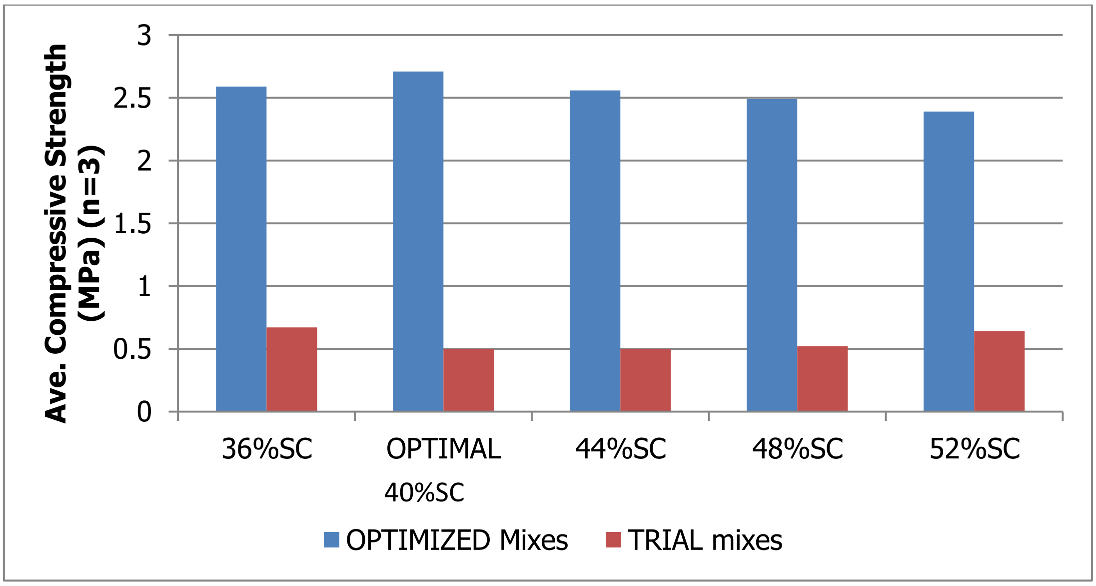


Fig 5.12: Comparison of the compressive strength of trial mixes and optimized mixes

5.4 COMPRESSIVE STRENGTH OF OPTIMAL CWLB

At optimum mix composition, CWLB displayed an average compressive strength of 2.71 MPa at 28 days curing age. The individual compressive strength recorded for three samples were 2.71 MPa, 2.73 MPa, and 2.69 MPa indicating a standard deviation of ±0.02 and the apparent reliability of the result.

In contrast with standard compressive strength requirement for non-loadbearing lightweight blocks; the 2.71 MPa average compressive strength exhibited by optimal CWLB is comparatively 81% higher than the 1.5 MPa minimum compressive strength recommended by BS EN 771-4:2011 for non-load bearing lightweight block. This result indicates that in terms of compressive strength, CWLB is suitable for use as a non-loadbearing block in building construction and can serve as a suitable alternative to other cement base non-load bearing blocks (e.g. AAC blocks and masonry blocks) that are presently being used for internal partitioning.

In addition, it is also interesting to note that the 2.71 average compressive strength displayed by CWLB (n=3) represents; 97% of the 2.8 MPa minimum average compressive strength recommended by (BS EN 6073-1:1981) for aggregate concrete blocks, and 93% of the 2.9 MPa compressive strength of the commercially available lightweight blocks in the UK construction industry. This indicates the potential of CWLB for higher load requirement with minimal strength improvement.

5.4.1 Review of Strength Development in CWLB

Figure 5.13 clearly shows that CWLB attained greater strength at optimum mix composition compared to other weaker optimized mixes (including OPT-M1, OPT-M3, OPT-M4, and OPT-M5). The lower strength displayed by OPTM1 (which contained 36% sand content by weight of WPA) may be attributed to the presence of pores spaces developed within its microstructure due to slight rebounding brought about by the insufficient quantity of sand (which if otherwise could have offset rebounding) and the excessive quantity of WPA in its mix composition.

Similarly, the lower strength developed by OPT-M3, OPT-M4, and OPT-M5 may be attributed to the excessive quantity of sand which reduces the bond between the WPA fibre/grains and thereby resulted in a less strong specimen. This indicates that CWLB attains greater strength at optimum processing parameter combination. It further implies that the intensity of the bond that exists amongst WPA fibres within the microstructure of CWLB specimen enact a crucial role in its strength development. These findings come in line with the literature reports regarding the basis of papercrete strength. Fuller (2014) had reported that the cellulose hydrogen bonding found in the matrices of wastepaper fibre forms the basis for papercrete strength. According to the same author, the cellulose chains which are packed together within the wastepaper fibre produces a hard, stable and crystalline region that provides greater stability and strength to the bundle of cellulose chain.

Evidence of the higher quality of optimal CWLB specimen compared to specimen produced from other weaker mixes was apparent in its UPV value. It was therefore deduced that sand as a constituent of CWLB functions more as a stabilizer and densifier rather than a strength modifier. Also, a relatively strong correlation can be reckoned to exist between the compressive strength and sand content of CWLB as the fitted polynomial regression line displayed an R2 value of 0.8445.

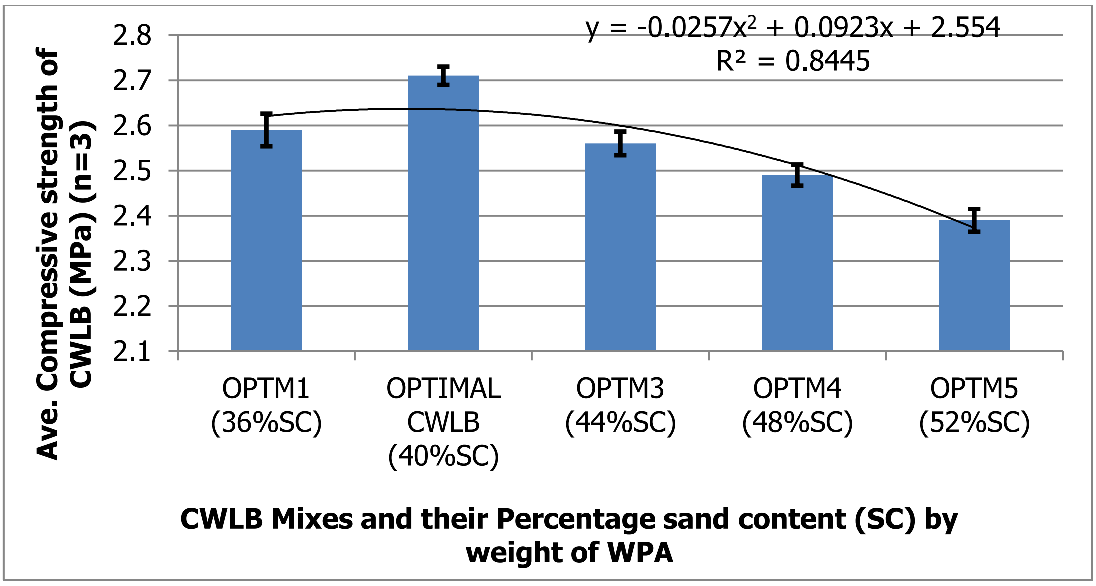


Fig. 5.13: Comparison of Optimal CWLB with the Four Optimised CWLB weak Mixes

5.4.2 Comparison of the Compressive Strength of CWLB with those reported for the existing Cement-Based Papercrete Blocks.

Figure 5.14 presents the compressive strength of optimal CWLB in contrast with the compressive strength of cement-based-wastepaper blocks (e.g. papercrete) available in the literature. It is interesting to note that despite the absence of cement in the mix composition of CWLB and the presence of 75% waste content in its constituent material, CWLB displayed maximally higher compressive strength compared to cement-based-wastepaper blocks produced with a lower amount of waste content. The 2.71 MPa average compressive strength displayed by OPTIMAL CWLB is;

- 47% higher than the 1.84 MPa (Modry, 2001) reported for papercrete block containing 40% by volume paper pulp
- 65% higher than the 1.64 MPa (Chandarana *et al.*, 2014) reported for papercrete block containing 1:1:2 paper:cement:sand ratio (corresponding to 25% paper, 25% sand and 50% cement) and

- 93% higher than the ≈1.4 MPa (Akinwumi *et al.*, 2014) reported for papercrete block containing 35.7% cement 35.7 sand and 28.6% Wastepaper (i.e. mix ratio 1: 1:0.8).

The assessment of CWLB,s eco-friedliness compared to papercrete blocks is presented in Appendix 2 of this thesis.

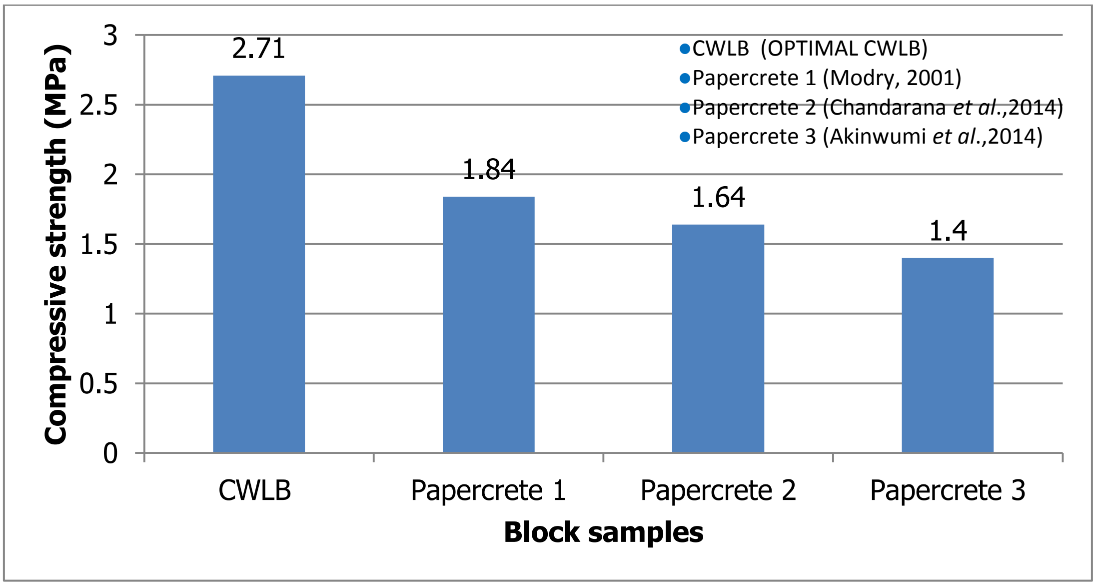


Fig. 5.14: Comparison of Compressive Strength of CWLB against Cement Based Papercrete Blocks.

5.4.2.1 Inferences from Optimization Compressive Strength of CWLB

The details of the optimization of the mixture composition of CWLB using Taguchi approach were presented in this section. CWLB specimens of sizes 50mmx 50mm x 50mm were moulded from mixture of WPA, sand, waste additive (binder), natural admixture and water. The control parameters which include; WPA/Sand ratio, Water/Binder ratio, and Compacting force were investigated with the aim of maximizing the 28 days compressive strength of CWLB. The outcome of the investigation showed that the compressive strength of CWLB depends on the processing parameters. Comparism of the main effect of WPA/Sand ratio, Water/Binder ratio and Compacting Force indicated that Water/Binder ratio has the most significant effect on the compressive strength of CWLB. The identified optimal parameter setting viz; 2.5 WPA/Sand ratio, 0.75 Water/Binder ratio, and 3.5 metric ton Compacting force produced CWLB specimen with properties suitable for non-load bearing application. The optimum mixture composition of CWLB which contains 62.5% WPA, 25% Sand and 12.5% waste additive (binder) indicates that CWLB possess 75% waste content and this characteristic makes CWLB a highly eco-friendly block in terms of its potential to contribute to natural resources conservation (Note the optimum mix composition of CWLB additionally contains 5% admixture measured by weight of WPA).

5.5 SUMMARY OF CHAPTER

This chapter presented the findings from two different experimentations that were conducted to address the second and the third objective of this research namely; the study of the salient parameters influencing the compressive strength of CWLB (see section 5.2) and the optimization of the mix composition of CWLB (see section 5.3).

The salient parameters influencing the compressive strength of CWLB were investigated to understand its behaviour and identify the crucial factors that need to be considered for the optimization of its mix composition to achieve a maximal compressive strength. This objective was achieved by employing the OFAT design of experiment approach and using the trial mixes derived from the preliminary experimentation as a baseline mix. Parameters which include; water content, binder content, curing ages, curing temperature, crushing orientation, and compacting forces were investigated and the findings from this study served as a basis for the subsequent optimization study.

The optimization study was conducted to determine optimum mix composition of CWLB and to maximize its compressive strength in order to satisfy the required standard. To achieve this, the Taguchi DOE was adopted with the use of the L_9 orthogonal array. Three crucial processing variables (identified from the salient parameter study) were simultaneously investigated while using the compressive strength as the response variable. At the end, the optimum mix composition for CWLB was obtained along with an intensified compressive strength that maximally satisfied the standard requirement for non-load bearing application. The optimum processing parameters obtained from this study were adopted to produce optimal CWLB specimens for the investigation of other engineering properties of CWLB.

CHAPTER SIX: RESUSLTS AND DISCUSSIONS

6.1 INTRODUCTION

This chapter presents and discusses in details, the properties of CWLB specimen produced using the optimal processing parameters obtained from chapter 6. It also presents the properties of stabilized wastepaper based lightweight block (SWLB) which is a cement stabilized version of CWLB.

6.2 OTHER ENGINEERING PROPERTIES OF OPTIMIZED CWLB

Having previously obtained and discussed the compressive strength of CWLB from the optimization study, the other engineering properties discussed in this chapter include:

1. Density
2. Dimensional check
3. UPV
4. Thermal conductivity
5. Capillary water absorption coefficient
6. Elastic modulus

Each test data presented in this work corresponds to the mean value of the three test CWLB cubic block specimens. The standard deviations are plotted on the test data points as the error bar. As mentioned in Chapter 3, the expected properties of lightweight non-load bearing blocks as specified by the BS 771-4:2011 were used as the major reference standard to ascertain the quality and suitability of CWLB for use as a lightweight non-load bearing blocks.

For consistency, tests such as compressive strength and UPV whose determination has to do with specimen orientation were determined using the as-cast side face orientation of CWLB specimen.

Each section therefore presents and discusses the properties of optimal CWLB and further evaluates the same against the:

- BS 771-4(2011) Standard requirements for lightweight non-load bearing blocks;
- Properties of four other "weaker" optimised CWLB mixes; and
- Previously published properties of cement-based wastepaper lightweight blocks (namely: Papercrete).

6.3 MIX COMPOSITIONS AND ENGINEERING PROPERTIES OF CWLB

For clarity of the results and the discussions presented in this chapter, the summary of mixture compositions for CWLB (including Optimum CWLB mix composition and the four weaker optimised CWLB mixes along with the summary of their engineering properties are presented in Tables 6.1 and 6.2 respectively.

Table 6.1: Details for CWLB Mix compositions and their Categories

CWLB Mixtures	Mix Designation	Mix ratio	Mix Details				Compacting force (Metric ton)	Curing age (days)
		WPA : S : B	Percentage Sand content (by wt. of WPA)	Percentage binder content (by wt. of WPA)	Water to binder ratio	Percentage Admixture content (by wt . of WPA)		
Optimized weaker mix composition	OPT-M1	1: 0.36 : 0.2	36%	20%	0.75	5%	3.5	28
Optimum mix composition	OPT-M2	1: 0.4 : 0.2	40%	20%	0.75	5%	3.5	28
Optimized weaker mix compositions	OPT-M3	1: 0.44 : 0.2	44%	20%	0.75	5%	3.5	28
	OPT-M4	1: 0.48 : 0.2	48%	20%	0.75	5%	3.5	28
	OPT-M5	1: 0.52 : 0.2	52%	20%	0.75	5%	3.5	28

Note: WPA=wastepaper Aggregate; S=sand; B=Binder (i.e. waste Lactose); wt=weight

Table 6.2: Summary of Engineering Properties of CWLB

CWLB Specimen	Ave. Compressive strength (MPa) (at 28 days) (n=3)	Density (Kg/m^3)	UPV (m/s)	Dimensional check	Thermal conductivity (W/m.k)		Coefficient of Capillary Water Absorption (C_w) $x10^{-4}$ ($g/(m^2 xS^{0.5})$)	Estimated Elastic modulus (MPa)
					min	max		
OPT-M1	2.59	881.7	946.5	Satisfactory	0.20	0.52	20	789.88
OPT-M2 (OPTIMAL CWLB)	**2.71**	**901.5**	**989.9**	**satisfactory**	**0.19**	**0.52**	**17**	**883.38**
OPT-M3	2.56	904.9	935.4	Satisfactory	0.19	0.52	16	791.76
OPT-M4	2.49	909.4	915.8	Satisfactory	0.19	0.52	23	762.70
OPT-M5	2.39	914.8	881.1	Satisfactory	0.19	0.52	22	710.19

6.4 DENSITY OF CWLB

The OPTIMAL CWLB displayed an average density of 901.5 kg/m^3 at 28 days curing age. As shown in Table 6.3, this density satisfied the density range of 300-1000 kg/m^3 (BS EN 771-4:2011) and 625 kg/m^3-1500 kg/m^3 (BS EN 2028 1975) specified for lightweight non-load bearing blocks. The densities displayed by the CWLB specimen is comparatively lower than the 1060.74 kg/m^3 average density (Akinwumi *et al.*, 2014) reported for papercrete block produced from 1:1:0.8 paper: cement: sand ratio. This indicates that CWLB possesses a higher strength to weight ratio compared to papercrete blocks. Based on reported real-life evidence from the construction industry, application of lightweight blocks in construction is capable of increasing productivity as well as reducing construction time. The less work intensive characteristics associated with the use of lighter blocks enables workers to be more efficient during construction (Brendan Quinn (2014) in Eberly and Drotleff, 2014). For example, the utilisation of a lightweight masonry block (known as E-Lite) containing 60% riverlite, 28% natural aggregate and 12% cement and water during the construction of a six new warehouse buildings at Maryland Science Center in Baltimore was reported to have reduced construction time and labour specifics to block erection by 50% (Eberly and Drotleff, 2014). It can, therefore, be envisioned that the application of CWLB in wall construction shall result in reduced construction period and low construction cost. Similarly, the 914.8 - 881.7 kg/m^3 average densities exhibited by other weaker optimized CWLB specimen were satisfactory with regards to the standard requirements (Table 6.3) and the trend showed that the density increases with increasing sand content (see Fig. 6.1). This indicates that sand added weight to the block. A regression trend line fitted to the graph of density against sand content showed that a relatively strong correlation exists between the density of CWLB and its sand content. R^2 was found to be 0.8602 indicating an r value of 0.927 and a linear relationship was established.

Table 6.3: Average densities of CWLB optimized weaker mixes and the BS standard requirement

CWLB Optimized weaker mixes	Average Density (Kg/m^3)	**Standard limit (BS 771-4:2011)**
OPT-M1	881.7	**300-1000 kg/m^3**
OPT-M2 (OPTIMAL CWLB)	**901.5**	
OPT-M3	904.9	
OPT-M4	909.4	
OPT-M5	914.8	

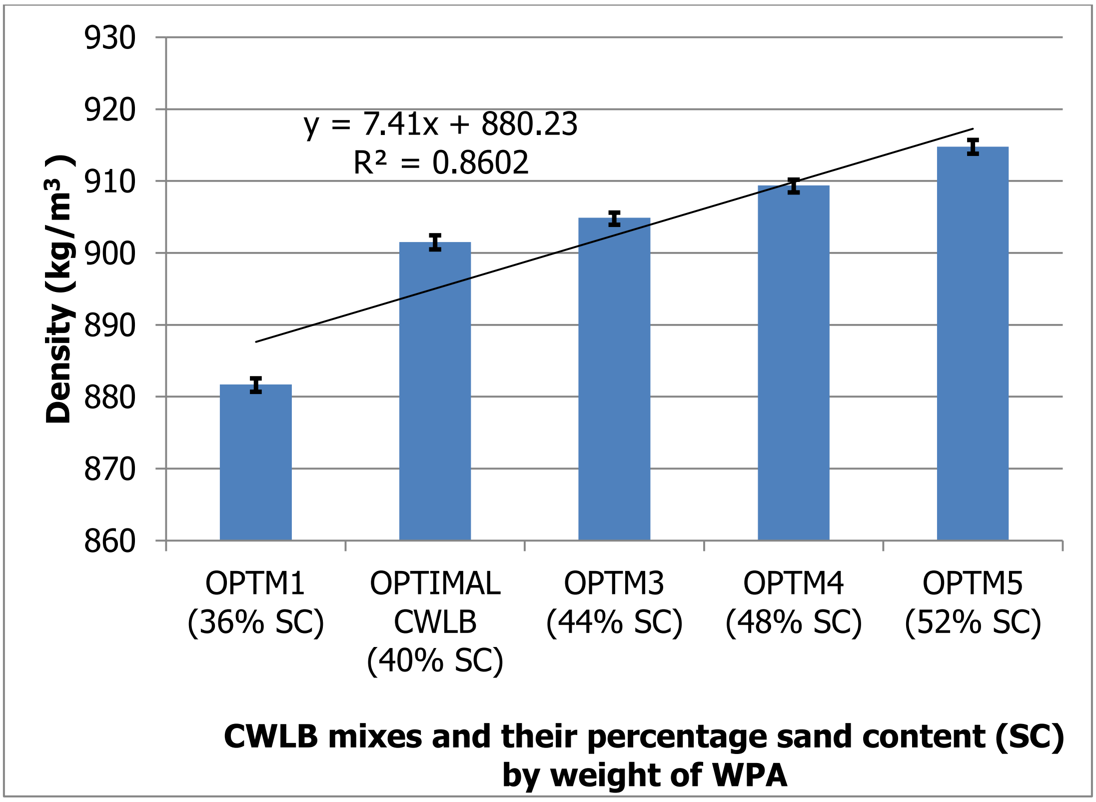


Fig 6.1: Effect of sand content on the density of CWLB

6.4.1 Relationship Between Density and Compressive Strength Of CWLB

Unlike cement-based building materials (e.g. masonry blocks) whose strength sometimes depend on its dried density, an unusual trend with a polynomial relationship was observed between the density and the compressive strength of CWLB. The R^2 value for the fitted polynomial trend line was found to be 0.8867 which indicates the existence of a relatively strong correlation. As presented in Fig. 6.2, the compressive strength of CWLB reached its optimum at 901.5 kg/m^3 and beyond this point, it decreases as the density increases. This implies that heightening the quantity of sand in the constituent of CWLB contributes to strength increase up to a point that can be regarded as optimum proportion, beyond which further increase in sand quantity causes reduction in compressive strength. It therefore appeared that CWLB derived its strength from the stiffness of WPA fibres and degree of compaction of constituent materials rather than from its mass per unit volume.

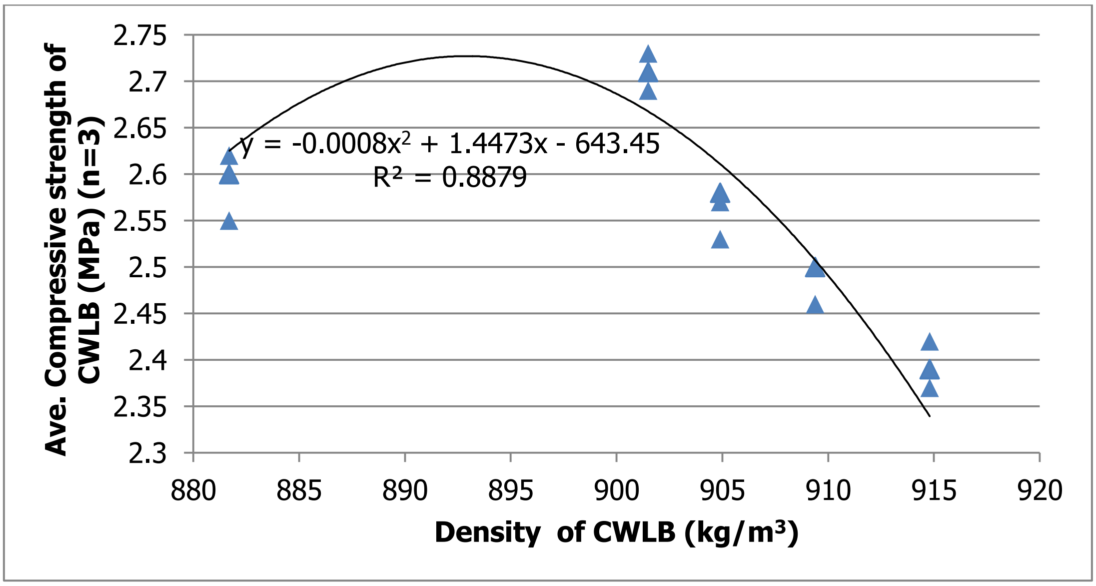


Fig. 6.2: Correlation between compressive strength and density

6.5 DIMENSIONAL STABILITY OF CWLB

To achieve an optimal use of block wall as structural element in building construction, the dimensional stability of the block utilized in constructing it must be such that satisfies the standard/specified allowable dimensional deviations of height, length, and width. For example, in the architectural design of building structure, spaces/room dimensions are usually designed to precisely accommodate multiple numbers of standard sizes of the block in a row, any discrepancies beyond the allowable deviation usually results in difficulties and excessive use of mortar. It is, therefore, paramount to ensure that block dimensions are relatively stable in order to enable the size of individual units to be controlled to within small tolerances.

As shown in Table 6.4, the measured dimensional deviation of CWLB specimen fully satisfies the acceptable standard length (L), height (H) and width (W) deviation limits specified by BS EN771-4:2011 (Section 5.2.2.1) for non-load bearing lightweight blocks units laid with general purpose mortar and thin layer mortar. As shown in Table (6.4) the OPTIMAL CWLB specimen displayed an average dimensional deviation of +0.5mm, +0.5mm and -0.5mm for the Length, Width, and Height respectively. The same amount of deviation was recorded for other weaker CWLB optimized mixes. This result signifies that CWLB specimens are dimensionally stable and are suitable for use as walling elements in building construction. The small deviation displayed on the length and width of the specimen may be attributed to the springback characteristics associated with densified biomass upon release of compacting pressure (Dhamodaran and Afzal, 2012) while the displayed deviation on the height may be attributed to mixture loss that may have occurred during mould filling. These deviations are within the standard limits. They can also be respectively prevented by ensuring that the internal dimensions (length and width) of the mould are designed to accommodate the expected negligible springback behaviours and that adequate quantity of fresh CWLB mixture is compacted during moulding.

Table 6.4: Dimensional Deviation of CWLB Specimen

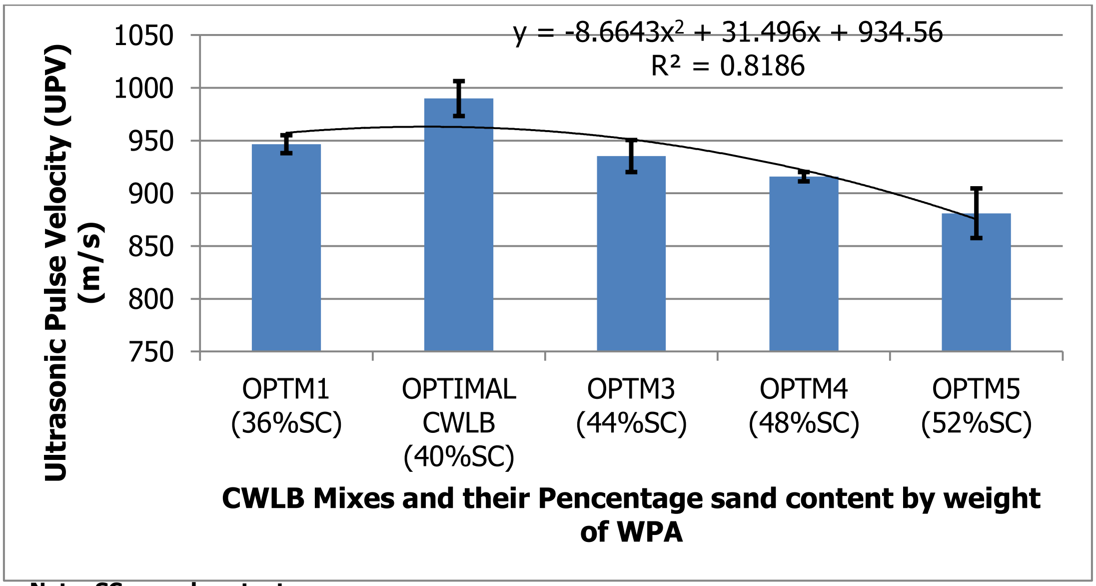
CWLB specimen		**Standard Limit (BS 771-4:2011)**
Measured Dimensional deviation Length, Height and Width (mm)		Permitted Dimensional Deviation Length, Height and Width (mm)
OPTM1	+0.5mm, -0.5mm and +0.5mm	
OPT-M2 (OPTIMAL CWLB)	**+0.5mm, -0.5mm and +0.5mm**	**±5mm, ±5mm, and ±3mm**
OPTM3	+0.5mm, -0.5mm and +0.5mm	
OPTM4	+0.5mm, -0.5mm and +0.5mm	
OPTM5	+0.5mm, -0.5mm and +0.5mm	

6.6 ULTRASONIC PULSE VELOCITY (UPV) OF CWLB

As shown in Table 6.5, an average UPV value of 989.9 m/s was obtained for 3 OPTIMAL CWLB (n=3) at 28 days curing age. According to literature, higher values of UPV indicate high quality of building materials in terms of strength and porosity, for instance, concrete specimen which exhibits UPV values greater than 4500 m/s are classified as being strong while those exhibiting 3500-4500 m/s, 2000-3500 m/s and less than 2000 m/s are classified as good, intermediate and weak respectively (Hammood, 2013). Presently, there are no specified limits of UPV values for neither wastepaper based building materials nor masonry blocks, however judging from the concept/trend that higher UPV values indicate higher quality (as apparent in UPV concrete classification), as shown in Fig. 6.3, the comparison of UPV value for OPTIMAL CWLB with other weaker optimized mixes shows that OPTIMAL CWLB is of higher quality in terms of strength, degree of compaction and porosity compared to other mixes. The observed percentage decreases are 6%, 8% and 11% for OPT-M3, OPT-M4 and OPT-M5 respectively compared to the OPTIMAL CWLB.

Table 6.5: Ultrasonic pulse velocity of CWLB

CWLB specimen	Average UPV (m/s)
OPT-M1	946.5
OPT-M2 (OPTIMAL CWLB)	**989.9**
OPT-M3	935.4
OPT-M4	915.8
OPTM5	881.1



Note: SC= sand content

Fig. 6.3: UPV of OPTIMAL CWLB and other CWLB optimized weaker mixes

6.6.1 Correlation of UPV and Compressive Strength of CWLB

The UPV values displayed by CWLB specimen are in agreement with the compressive strength results obtained, in the sense that, at 28 days curing age CWLB specimen exhibiting higher compressive strength displayed higher UPV values while those exhibiting lower compressive strength displayed a corresponding lower UPV values. As shown in Fig. 6.4, a similar trend with a linear relationship was observed between the compressive strength and the UPV of CWLB. The R^2 for the fitted linear trend line was found to be 0.9773 which indicates an r value of 0.9886 and the apparent existence of a strong relationship between the two parameters. This means that in real-life application UPV test results could be used to estimate the expected compressive strength of CWLB on site in the absence of compression test equipment using the Eqn. 6.1 obtained from the fitted regression line as follows.

$y = 0.0024x + 0.2708$ ……………………………………………………………..(6.1)

Where

y= compressive strength of CWLB at 28 days curing age (MPa)

x=UPV of CWLB at 28 days curing age (m/s)

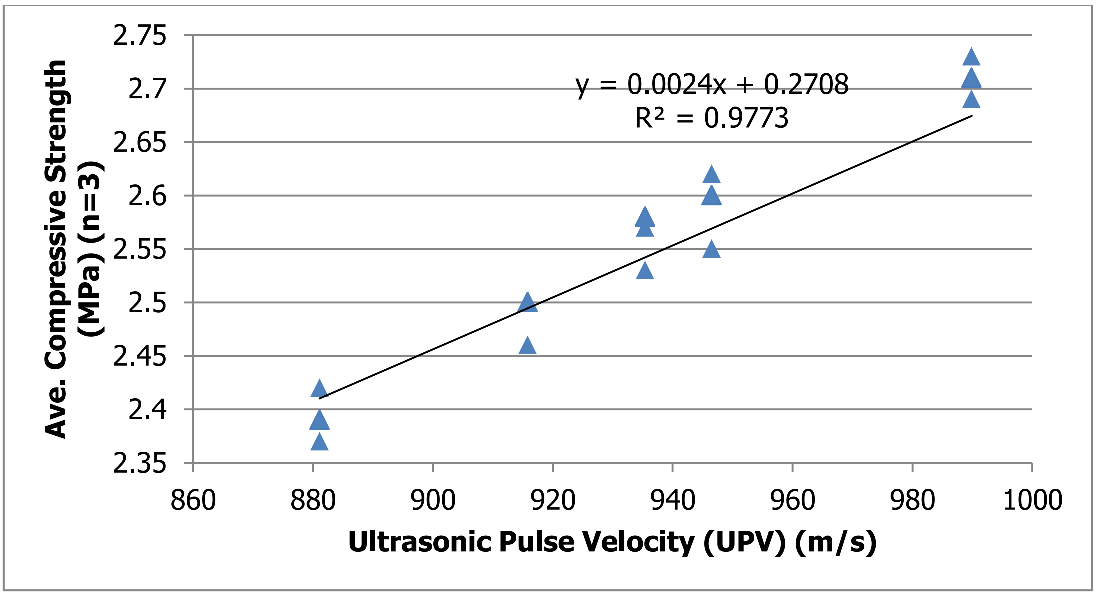


Fig. 6.4: Relationship between the Compressive strength and UPV of CWLB

6.7 CAPILLARY WATER ABSORPTION OF CWLB

Capillary rise is a mechanism that describes the penetration of water from the groundwater into a building material (e.g permeable wall) in an upward vertical direction (Alfano *et al*., 2006). For a building material to function effectively during its service life, the knowledge of its coefficient of capillary water absorption (which is defined as the rate of absorption of water into building material due to capillary forces) is important as it enables the determination of its hydrometric properties. Karagiannis *et al*., (2016) rationalised that moisture related problem in building can be effectively offset through the provision of adequate preventive measure at the design stage. The CWLB developed in this study is not expected to be exposed to the weather elements since it is designed to be used for non-load bearing application. However, being a novel building material, it became paramount to find out its sorptivity coefficient in order to determine its capillary water absorption capacity with the objective of making appropriate recommendation for its installation.

Figure 6.5 shows the amount of water absorbed per unit area for OPTIMAL CWLB and its weaker mixes at 28 days curing age during the first hour, and Fig. 6.6 shows the coefficient of capillary water absorption (i.e. the slope of the initial part of the curve presented in Fig. 6.5 for each of the CWLB mixes. The amount of water uptake in CWLB differs for mixes with varying sand content. For instance, OPTIMAL CWLB and OPT-M3 which both contains 40% and 44% sand content (by wt. of WPA) respectively displayed the lowest amount of water uptake per unit area, while OPT-M1, OPT-M4 and OPT-M5 which contains 36%, 48%, and 52% sand content (by wt. of WPA) respectively shows substantial water uptake per unit area. Also, as shown in Figure 6.6, the rate of water uptake (i.e. coefficient of capillary water absorption) is higher for OPT-M1, OPT-M4 and OPT-M5 compared to the OPTIMAL CWLB and OPT-M3. This indicates that there is higher capillary absorption in CWLB when incorporated with more than 44% sand content compared to those containing less than 44% sand content.

Research has shown that waste paper pulp absorbs water at a rapid rate with increasing immersion time. Salem and Al-Salami (2016) reported that the cellulosic characteristics of wastepaper makes the wastepaper pulp in papercrete to absorb a considerable amount of liquid immediately it comes in contact with water prior to the commencement of capillary forces which after some time additionally conduct water molecules in the material to fill the void spaces.

It should be noted that CWLB contains wastepaper fibre which is a highly hygroscopic material, therefore its reaction to water is apparently expected to be different from the reaction of other materials (like masonry block or concrete block) to water. As shown in Fig. 6.6b CWLB absorbed a considerable amount of water after 5 minutes of exposure. Its lowest coefficient of capillary water absorption (C_w) ranges between [(0.0025 to 0.0026) g/(m^2 x $s^{0.5}$)], [1.e. (2.5x10^{-6} to 2.6$10^{-6}$) kg/m^2x$s^{0.5}$].

This finding generally indicates that CWLB absorbs water at a high rate. A similar observation has been reported for most wastepaper based blocks (namely, papercrete) (Akinwumi *et al*., 2014; Yun *et al*., 2007). The 2.6x10^{-6} kg/m^2 x $S^{0.5}$ average C_w recorded for optimal CWLB is comparable to the 0.8 kg/m^2x$min^{0.5}$ average C_w reported by Canola *et al*., (2012) for papercrete panel containing 25% wastepaper content and 75% cement content. It is also comparatively lower than the 0.0254 kg/m^2.$S^{0.5}$ reported by Niemz (2010) for a 19mm thick fibre board of density 670 kg/m^3 tested along the fibre direction and lower than the 0.0014 kg./m^2.$S^{0.5}$ obtained when tested perpendicular to the fibre direction for the same specimen (Niemz, 2010). It is therefore recommended that CWLB should not be used near-ground walls (i.e. substructure) because of its high capillary water absorption coefficient. Similar to the recommendation for papercrete which previously published literature have reported to exhibit high water absorption (Akinwumi *et al*., 2014). CWLB is recommended for use above 1m ground level of non-load bearing wall and should possibly be installed on a damp-proof membrane as well as covered with plastering mortar in order to prevent the capillary rise of water from the ground into its microstructure.

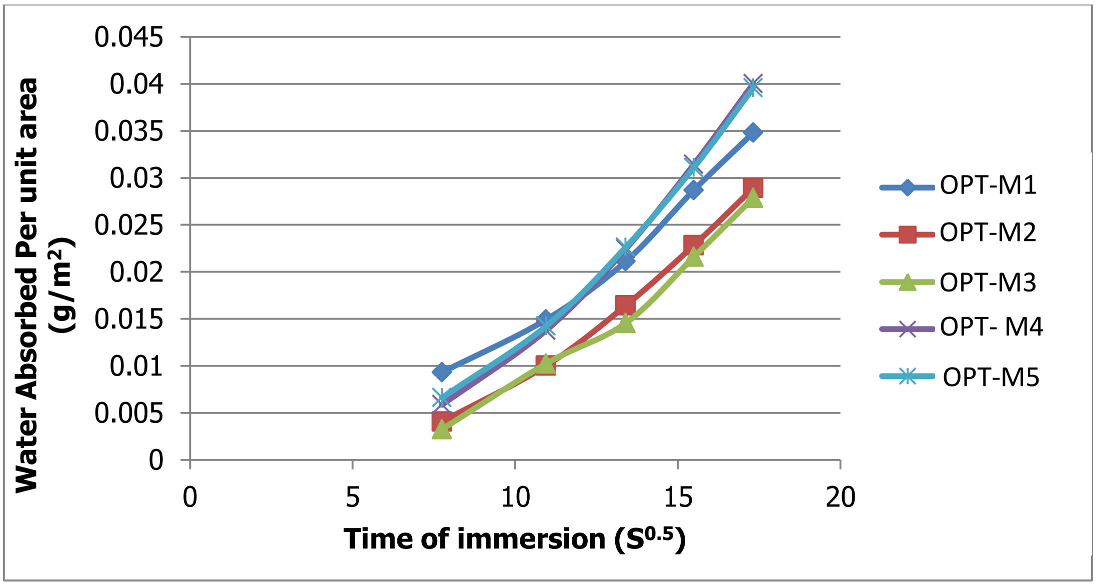


Fig. 6.5 : Capillary water absorption per unit area of CWLB

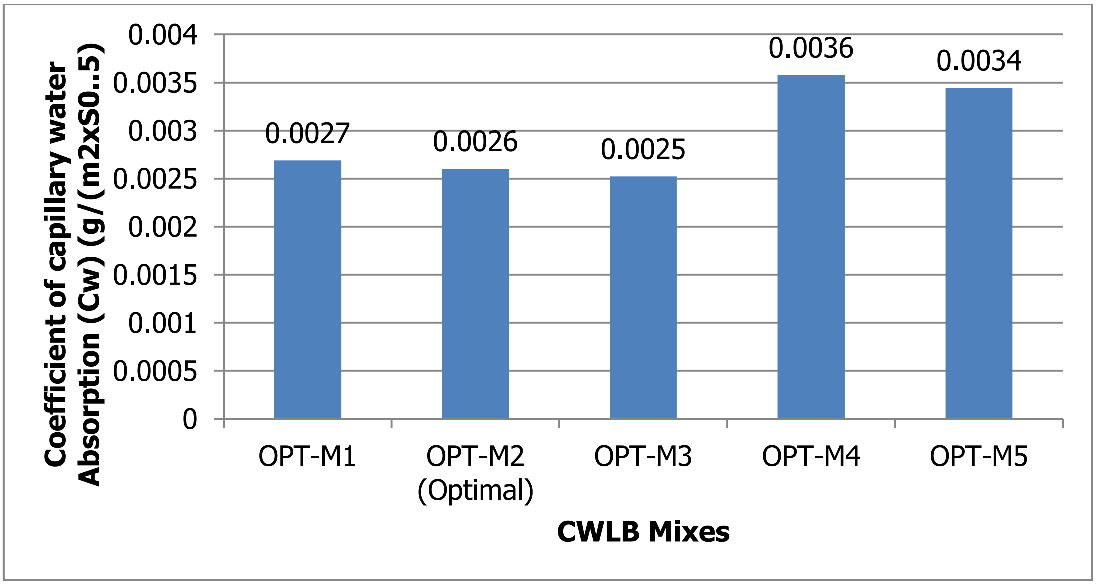


Fig. 6.6 : Coefficient of capillary water absorption of CWLB

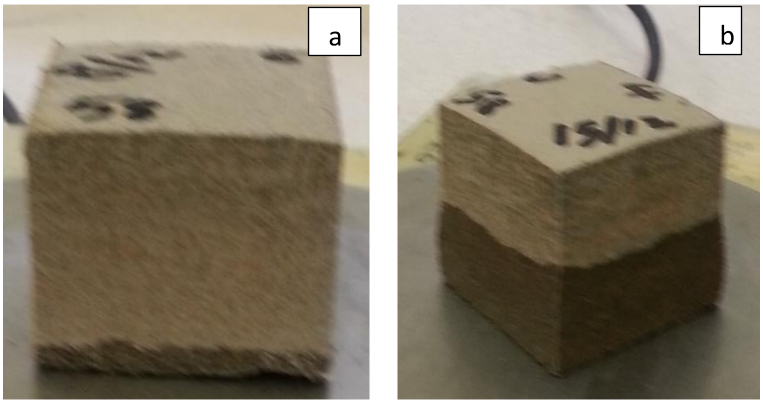


Figure 6.6b: Capillary water absorption of CWLB at; (a) 1min, and at (b) 5min of exposure to water

6.7.1 Correlation of Compressive Strength and Capillary Water Absorption of CWLB

As shown in Fig. 6.7, the coefficient of capillary water absorption (C_w) of CWLB relatively agrees with its compressive strength values in the sense that CWLB specimen that exhibited higher compressive strength displayed a corresponding lower rate of water absorption (i.e. lower coefficient of capillary water absorption), while those that exhibited lower compressive strength absorbed water at a higher rate. For example, the C_w is apparently higher for OPTM4 and OPTM5 while it is lowest around OPTIMAL CWLB and OPTM3. However, as shown in Fig 6.8 the fitted polynomial regression line displayed an R^2 value of 0.5684 which indicate a very weak correlation between the two properties.

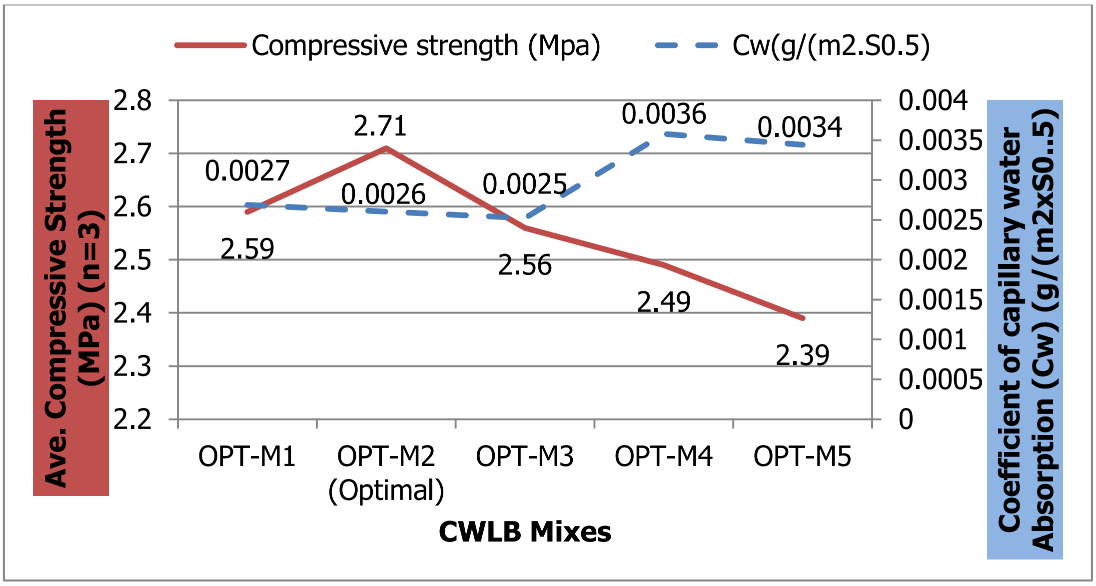


Fig. 6.7: Agreement between compressive strength and Coefficient capillary of Water absorption (Cw) of CWLB

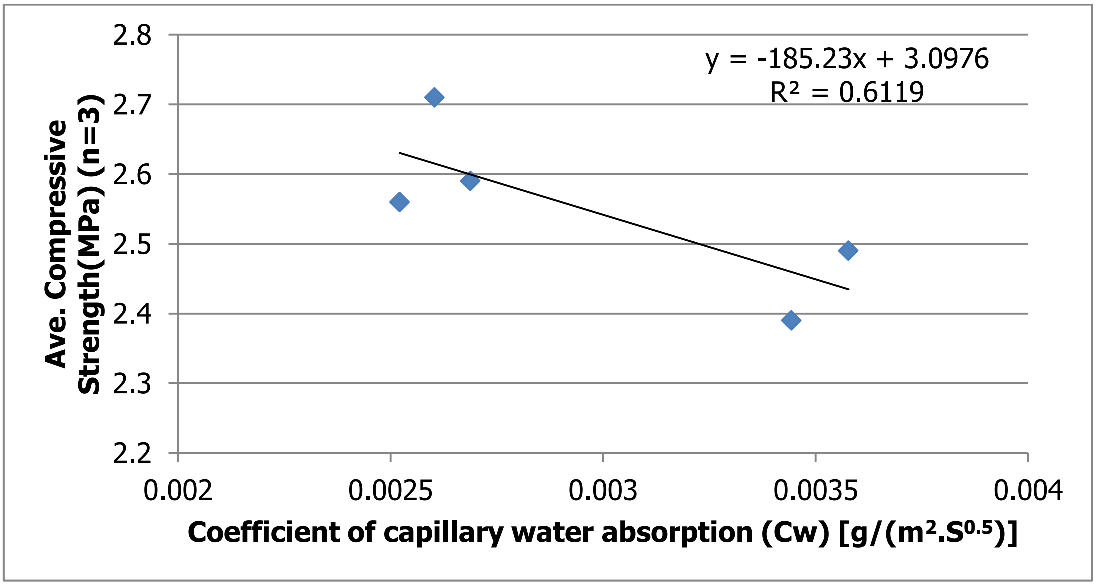


Fig. 6.8: Correlation of Compressive strength and coefficient of capillary water absorption (C_w) of CWLB

6.7.2 Correlation of Capillary Water Absorption and UPV of CWLB

As shown in Fig. 6.9, the coefficient of capillary water absorption of CWLB relatively agrees with its UPV values in the sense that CWLB specimen that exhibits higher UPV values displayed a correspondingly lower rate of water absorption (i.e. lower coefficient of capillary water absorption), while those that exhibited lower UPV values absorbed water at a higher rate. For example, the C_w is apparently higher for OPTM4 and OPTM5 while it is lowest around OPTIMAL CWLB and OPT-M3.

However, as shown in Fig. 6.10 the fitted linear regression line displayed an R^2 value of 0.4683 which indicate a very weak correlation between the two properties. This can be attributed to the unusual behaviour of CWLB due to its peculiar constituent materials (i.e. the presence of wastepaper fibres) which contributed to its water absorption apart from the porosity.

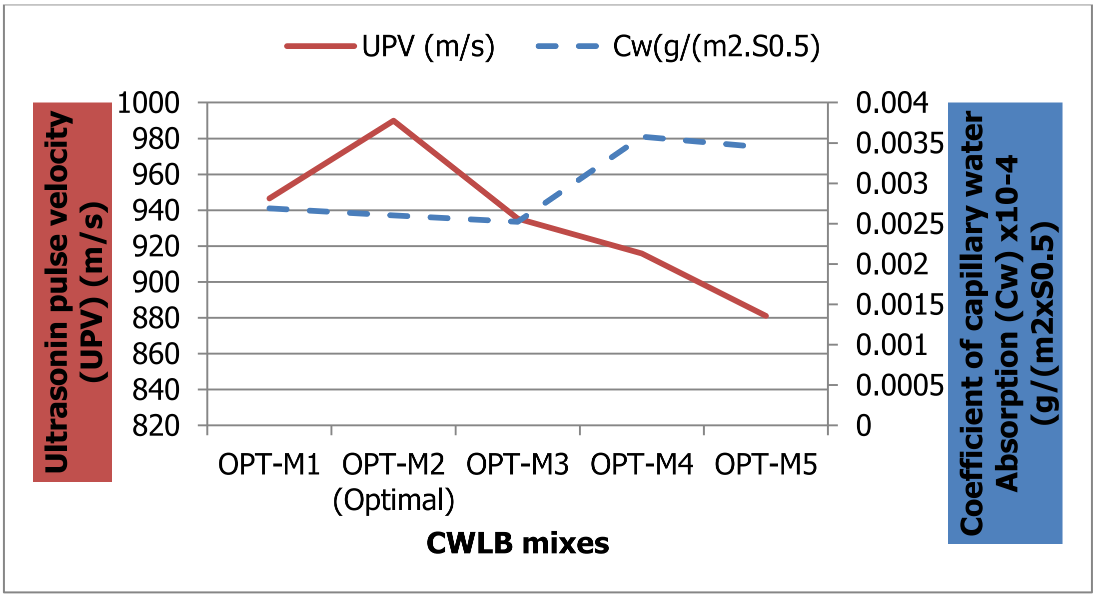


Fig. 6.9: Agreement between UPV and coefficient capillary of water absorption (C_w) of CWLB

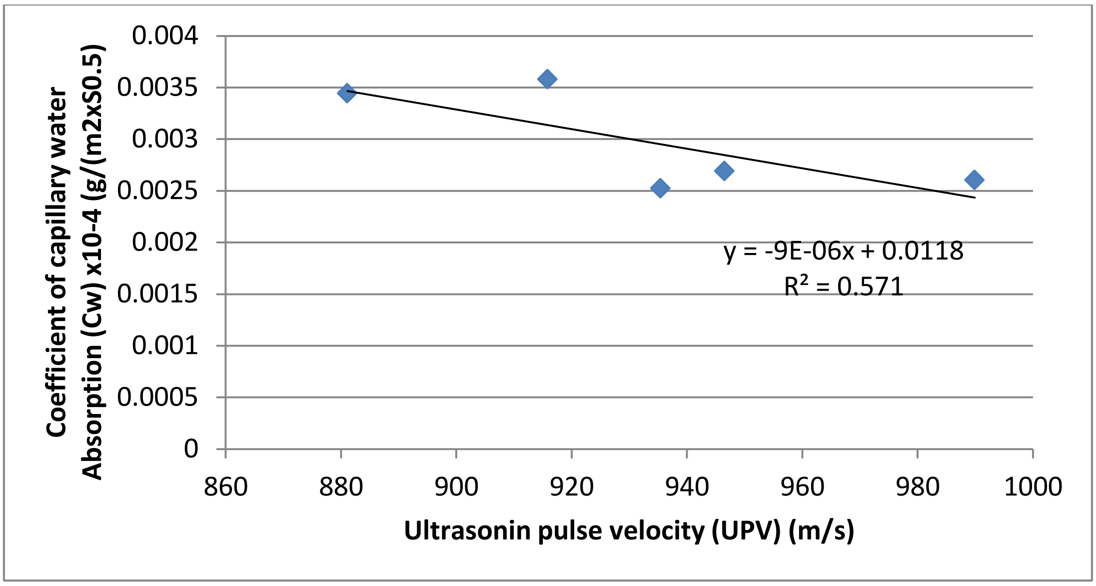


Fig. 6.10: Correlation of UPV and coefficient of capillary water absorption (C_w) of CWLB

6.8 THERMAL CONDUCTIVITY OF CWLB

The energy eco-efficiency of a building can be described as the ability of a building structure to maintain a temperature that is acceptable, uniform and comfortable indoor regardless of the climatic condition. BS EN771-4:2011 recommends that the information on the thermal properties of masonry units (measured in accordance with EN1745) be provided when such masonry unit is intended for use in element subjected to thermal requirement.

Also, the knowledge of thermal properties of a building material is required to understand the energy conservation properties that such building material will display during real application. Considering the disparity in the constituent materials of building elements and the modes of operation of different building structures, the thermal performance of a building is largely influenced by the thermal properties of its components (Asdrubali *et al.*, 2015).

Table 6.6 shows the thermal conductivity of OPTIMAL CWLB and its weaker mixes after 28 days curing age. The result shows that OPTIMAL CWLB and three other weaker mixes (OPT-M3, OPT-M4, OPT-M5) exhibit a thermal conductivity of 0.19 W/(m.K) and 0.52 W/(m.K) at steady state heat flow of 10 W and 20 W respectively. OPTM1 on the other hand, displayed thermal conductivity of 0.20 W/(m.K) and 0.52 W/(m.K) when the quantity of heat supply was 10W and 20W respectively. Based on this result, it is apparent that CWLB is a good insulator and its utilisation as a wall element in building structures will result in energy conservation both for the building owners and the environment at large.

In contrast with cement-based wastepaper blocks (namely; Papercrete) CWLB displayed comparable/similar thermal conductivity with papercrete and a much lower thermal conductivity compared to concrete and masonry blocks. Titzman (2006) in his research reported thermal conductivity of 0.10 W/ (m·K) for papercrete containing 20%-40% wastepaper content, Modry (2001) reported 0.35 W/m.k for papercrete containing 40% wastepaper content, Mohamed (2009) reported 0.85 W/m.k for papercrete containing 25% wastepaper content, and the thermal conductivity for concrete and masonry ranged between 1.25 and 1.75 W/ (m·K) (Titzman, 2006). This indicates that CWLB exhibits much lower thermal conductivity than concrete; and as such, its insulation value is much higher. It can be envisioned that the application of CWLB as non-load bearing wall element will result in thermal comfort for building occupiers and energy conservation for the environment.

Table 6.6: Thermal conductivity of CWLB

Heat Supply (W)	**Thermal conductivity (W/m.K)**				
	CWLB Mixes				
	OPT-M1	OPTIMAL CWLB	OPT-M3	OPT-M4	OPT-M5
10W	0.20	0.19	0.19	0.19	0.19
20W	0.52	0.52	0.52	0.52	0.52

6.9 ELASTIC MODULUS OF CWLB

Modulus of elasticity is a property that measures the deformation of a structural element of a building material. It is also a fundamental factor in determining the modular ratio n, commonly utilized for the design of structural members subjected to flexures. Also, for a masonry structure design to adequately comply with serviceability specification, the knowledge of elastic modulus of a masonry unit is required for determination of elastic deformation due to first application of load and for estimating creep arising from sustained load (Brooks, 2014)

As explained in Chapter 3, the elastic modulus of CWLB was estimated using the expression in Eqn. 6.2 which is grounded on the principle of ultrasonic pulse velocity testing described by BS1881-203:1986 and BS 12504-4:2004 in conjunction with the Newton-Laplace acoustic theory.

$$E = \rho {V_p}^2 \qquad \text{---} \ (6.2)$$

Where:

E= Elastic modulus (MPa)

V_p = Ultrasonic pulse velocity (m/s)

ρ =Density (kg/m^3)

It is believed that the expression in the equation above can give a near accurate estimation of the modulus of elasticity of CWLB considering that it was estimated based on known/experimentally determined properties of CWLB viz: density and UPV. It should, however, be noted that the values of E obtained for CWLB are estimates to give an idea of what its actual elastic properties could be. The actual values of E for CWLB will be determined via main laboratory experimentation in future research.

Table 6.7: Estimated Elastic modulus of CWLB

CWLB specimen	**Density kg/m^3**	**Average UPV (m/s) (n=3)**	**Estimated Elastic modulus (MPa)**
OPTIMAL CWLB	901.5	989.9	883.38
OPTM1	881.7	946.5	789.88
OPTM3	904.9	935.4	791.76
OPTM4	909.4	915.8	762.70
OPTM5	914.8	881.1	710.19

Table 6.7 presents the estimated elastic modulus of CWLB specimens, the results show that the OPTIMAL CWLB exhibits the highest modulus of elasticity of 883.4MPa while the OPTM5 displayed the lowest elastic modulus of 710.19 MPa. In contrast with cement-based wastepaper block, the estimated elastic modulus for all CWLB mixes is maximally higher than the 800 psi (5.52 MPa), 700psi (4.83 MPa), 590 psi (4.07 MPa) reported by Fuller *et al.*, (2006) and Santamaria *et al.*,

(2007) for papercrete produced from paper-cement-sand of; 1:1:5 gal, 1:1:10 gal and 1:1:15 gal respectively. The estimated Poisson ratio of CWLB was assumed to be zero at the assumed condition of uniaxial compression.

6.10 STABILIZED WASTEPAPER BASED LIGHTWEIGHT BLOCK (SWLB)

Having established the various engineering properties of CWLB at optimum mixture composition, the effect of cement addition on the properties of CWLB was evaluated by adding (2% - 10%) of cement (measured by weight of WPA) to the constituents of OPTIMAL CWLB. The resulting cement stabilized version of CWLB specimen produced from this experimentation was designated as stabilized wastepaper based lightweight block (SWLB). As shown in Table 6.8, SWLB1, SWLB2, SWLB3, SWLB4, and SWLB5, represents specimen containing 2, 4, 6, 8 and 10% cement (by wt. of WPA) respectively.

This section presents the properties of SWLB and evaluates them against the properties of; CWLB, commercially available lightweight block (e.g AIRTECH XL) and the British standard requirements for blocks.

Table 6.8: Effect of cement addition (by weight of WPA) on the compressive strength of wastepaper lightweight block

Optimal CWLB Mix ratio	**SWLB Mixture Details**		**SWLB Strength Properties**	
WPA : Sand :Binder	Added cement (% by weight of WPA) (%)	ID for Modified Mixes	Average density (kg/m3) (n=3)	Average Compressive strength (MPa) (n=3) (at 28 days)
1 : 0.40 : 0.20	2	SWLB1	904	2.70
1 : 0.40 : 0.20	4	SWLB2	910.4	2.76
1 : 0.40 : 0.20	6	SWLB3	912.5	2.82
1 : 0.40 : 0.20	8	SWLB4	918.1	3.00
1 : 0.40 : 0.20	10	SWLB5	920	3.48

6.10.1 Effect of Cement on the Compressive Strength of CWLB

The compressive strength of SWLB increases with increasing cement content. This result generally indicates that the introduction of cement to stabilize OPTIMAL CWLB had a significant effect on it compressive strength as can be appreciated from Figure 6.11. The result shows that at zero and 2% cement content, the average compressive strength was approximately 2.7 MPa. With an introduction of 4, 6, 8 and 10 percent cement content, the average compressive strength increased by 2%, 4%, 11% and 29% respectively. The improvement appeared to be rapid between 6% and 8% as well as between 8% and 10% cement content. This indicates that the compressive strength of SWLB increases with increasing cement content and the highest strength was obtained at 10% cement content. Building materials containing cement usually develop strength with continued hydration (AbdElaty, 2014). The higher strength displayed by SWLB at increasing cement content can be attributed to the process of cement hydration that must have taken place within its microstructure during curing.

It was observed that the compressive strength displayed by SWLB containing 2% and 4% cement content is comparable and in close range with the compressive strength of optimal CWLB. This implies that the strength property of CWLB exhibits the potential to be improved with the minimal addition of strength modifying admixtures, additives or cement as the case may be.

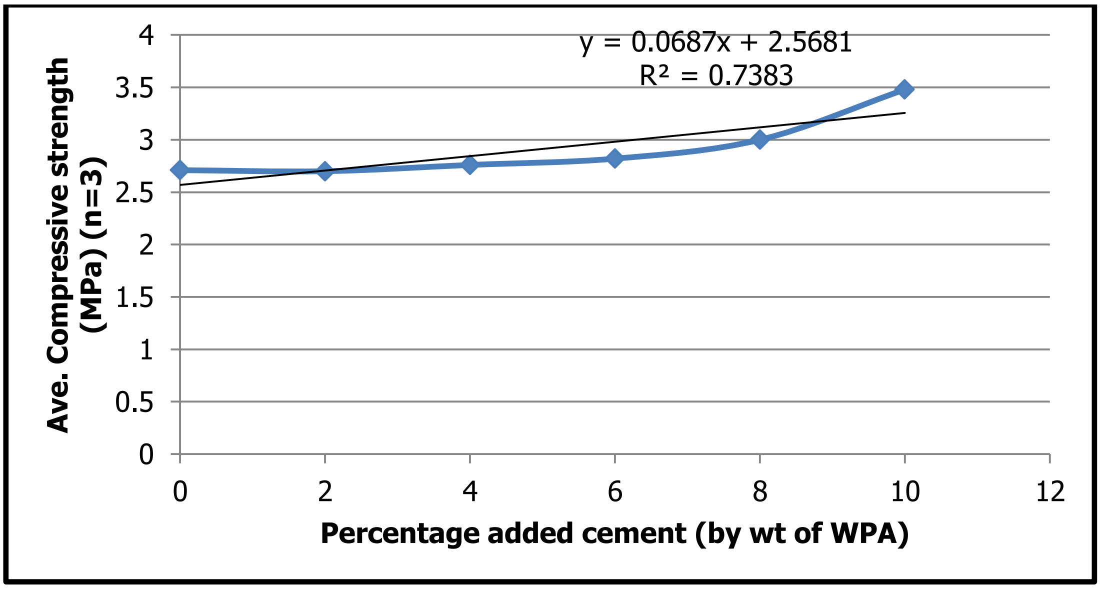


Fig. 6.11: Effect of Cement on the compressive strength of CWLB

6.10.2 Compressive Strength of SWLB in Contrast with BS Standard Requirement for Masonry blocks.

Similar to the compressive strength of OPTIMAL CWLB (which contained 0% cement) at 28 days curing age, the 2.7 and 2.76 MPa average compressive strength displayed by SWLB1 and SWLB2 specimen (stabilized with 2% and 4% cement content respectively) maximally satisfied the minimum requirement of 1.5 N/mm^2 specified in EN771-4:2011 for lightweight non-load bearing block and respectively attained 96% and 98% of the minimum requirement of 2.8 MPa specified in EN 6073,(1981) for aggregate concrete blocks. On the other hand, the respective average compressive strength of 2.82 MPa, 3.00 MPa, and 3.48MPa displayed by SWLB3, SWLB4, SWLB5 fully satisfies the 2.8 MPa minimum strength requirement specified by EN 6073 (1981) for aggregate concrete block. These results indicate the potential of SWLB for lightweight structural application at minimal cement content range of 6-10% (by wt. of WPA).

6.10.3 Properties of SWLB5 in Contrast with Properties of Optimal CWLB

The properties of SWLB5 which contained 10% cement content in contrast with the properties of optimal CWLB are presented in Table 6.9 below. The presence of cement in SWLB5 generally improved its properties in most cases when compared to the properties of CWLB except in the case of thermal conductivity where an equivalent result was obtained. Also, higher improvement was observed in compressive strength when compared to the percentage difference in other properties. For instance, SWLB5 displayed an average compressive strength of 3.48 MPa which corresponds to 28% strength increase in contrast with the 2.71 MPa displayed by the optimal CWLB while a marginal increase of 6% and 1% were respectively observed in the UPV and density of SWLB compared to that of optimal CWLB. The low percentage difference in the UPV and density of SWLB5 and CWLB may be attributed to the negligible quantity of cement incorporated in the SWLB5 which in the case of UPV must have enacted minimal effect in reducing the porosity of the specimen and contributed insignificantly to the density of the specimen making it to retain its lightweight physical property.

In the case of capillary water absorption, the SWLB surprisingly displayed 29% higher C_w compared to the OPTIMAL CWLB. This may be attributed to the presence of cement in SWLB.

Considering the minute proportion/percentage (typically 6%) that the added cement represents in the total composition of CWLB (Table 6.10) and the corresponding strength improvement, it was therefore inferred that CWLB exhibits the potential for significant, cost-effective and sustainable strength improvement.

Table 6.9: Comparison of SWLB and Optimal CWLB properties.

Properties	SWLB	CWLB	% difference
Ave. Compressive strength (n=3) (at 28 days)	3.48 MPa	2.71 MPa	28% increase
UPV	1049.7 m/s	989.9 m/s	6.04% increase
Density	910kg/m3	901.5 kg/m3	1% increase
Capillary water absorption coefficient (C_w)	22×10^{-4} g/(m^2 x $s^{0.5}$)]	17×10^{-4} g/(m^2 x $s^{0.5}$)]	29% increase
Elastic modulus	1002.7 MPa	883.38 MPa	13% increase
Thermal conductivity	0.19-0.52 W/m.k	0.19- 0.52 W/m.k	

Table 6.10: Typical mix composition of SWLB5 (presented in: Ratio; Percentage content and Measured Weight)

Measurement	Constituents proportions				
	WPA	**Sand**	**Binder(Waste additive)**	**Admixture (clay)**	**Cement**
Ratio	1	0.4	0.2	0.05	0.1
Percentage content (%)	57.1	22.9	11	3	6
Measured weight (g)	300	120	60	15	30

6.10.4 Properties of SWLB5 in Contrast with Commercially Available Lightweight Blocks in the UK

Table 6.11 presents the comparison of the properties (more importantly compressive strength) of SWLB5 with commercially available AAC block. In contrast with commercially available lightweight blocks in the UK construction industry (e.g. AIRTEC XL being manufactured by Thomas Armstrong LTD), the

3.48MPa average compressive strength displayed by SWLB5 is 20% higher than the 2.9MPa average compressive strength reported by Thomas Armstrong LTD (undated) for AIRTEC XL block. This indicates that at 10% cement content, SWLB exhibits higher/comparable strength with commercially available block designed for internal partition. This indicates its suitability for the intended purpose and the potential for future implementation/acceptability by stakeholders in the construction industry.

Table 6.11: Comparison of SWLB5 with commercially available AAC block

Properties	SWLB	AIRTEC XL
Compressive strength	3.48 MPa	2.9 MPa
UPV	1049.7 m/s	Not reported
Density	910 kg/m^3	460 ± 50
Capillary water absorption coefficient (C_w)	22x10^{-4} g/(m^{2}xs$^{0.5}$)]	Not reported
Elastic modulus	1002.7 MPa	Not reported
Thermal conductivity	0.19-0.52	0.09

6.11 SUMMARY

This chapter presented the engineering properties of CWLB and its cement stabilized version designated as SWLB. The properties presented were determined in accordance with the relevant British standards.

The results obtained showed that in all properties investigated, CWLB displayed maximally satisfactory properties when compared with the standard requirements for non-load bearing lightweight blocks. Also, CWLB was found to exhibit maximally higher strength properties compared to the cement-based wastepaper blocks (papercrete) available in the literature. The SWLB also displayed satisfactory properties in all cases and the high compressive strength displayed by

SWLB at lower cement content indicated the potential suitability of CWLB for higher strength intensive applications with minimal stabilization.

Based on these findings, CWLB can be regarded as an eco-friendly block, considering the presence of 75% waste content (see Appendix 2) and the absence of cement in its mix composition. It could therefore serve as suitable alternative to the cement-based and natural resources-intensive materials presently being used for non-load bearing application in non-structural wall construction.

CHAPTER SEVEN: MODELLING AND SIMULATION OF THE COMPRESSIVE LOAD CARRYING CAPACITY OF CWLB INSITU SOLID AND HOLLOW SAMPLES

7.1 INTRODUCTION

In the engineering field, newly developed products or parts are usually subjected to laboratory tests for determination of relevant engineering properties. After this, the same product is expected to be tested in the field to understand its behaviour and performance in the real life situation. In some cases, the process of real life testing of a novel product could become complicated and/or impossible due to limitations or depending on circumstances and the expected outcome of such investigation. According to Banks *et al*. (2010) a novel product (or system) may be; large and complex or dangerous to impose conditions for real study and observation. The same author stated further that in the process of real life study of a system, it sometimes become impracticable to isolate an expensive/essential system from service and that notional systems are devoid of physical components to perform experiments. These facts explain the reasons why experts in the engineering fields have developed a process known as simulation modelling with the main purpose of accurately mimicking the system under study. Such developed models are therefore investigated to learn more about the newly developed system.

It is on this wise that numerical modelling was carried out in this research to determine the approximate load carrying capacity of Finite Element model sample of CWLB insitu solid and hollow samples. This chapter presents the modelling process and the results obtained. Section 7.1 (along with Appendix 3) presents fundamentals of simulation modelling and finite element modelling. Section 7.1 to

7.2 presents the details of the analysis method and approaches employed for the simulation modelling. Section 7.3, 7.4, 7.5, and 7.6 presents the findings, discussions, inferences and the summary of the chapter respectively.

7.2 RATIONALE FOR SIMULATION MODELLING OF CWLB

In the development of a new product, circumstances relating to; cost, resources and safety may render the process of building and experimenting with new system to be impracticable or expensive (Sanchez, 2007). In the case of CWLB being developed in this research, constraint relating to unavailability of relevant equipment have rendered the production of a typical insitu representative sample of CWLB (e.g. hollow and solid samples) to be impossible. For this purpose, a three dimensional nonlinear finite element analysis of the compression process of CWLB was carried out with the aid of ABAQUS v6.13 (2013), the accuracy of the compressive load predicted by the chosen FEM analysis procedure was verified against the experimentally obtained compressive load of the CWLB laboratory tested specimen. In the literature, this kind of approach has been adopted for assessing the precision of numerical models developed to simulate the crushing load of different kinds of building materials including; foamed concrete cube specimen under uniaxial compression load (Goh *et al*., 2014), steel tube-confined concrete (STCC) stub columns subjected to axial load (Haghinejad and Nematzadeh, 2016), short concrete filled steel tubular (CFST) columns (Gupta and Singh, 2014) etc.

7.3 DETAILS OF SIMULATION MODELLING OF CWLB

The simulation program and methodology approaches followed to simulate the uniaxial compression of CWLB for the purpose of determining the approximate crushing load for finite element model of its insitu solid and hollow sample are presented in this section.

7.3.1 Methodology Approach

In order to determine the crushing load of CWLB Finite element model, various trials finite element modelling (FEM) analyses were first conducted on a 50mmx50mmx50mm 3D model prototype of CWLB for the purpose of identifying the suitable parameter setting (e.g. mesh density and loading velocity) for the simulation. A similar approach had previously been adopted by Goh *et al*. (2014) to study the behaviour of lightweight foamed concrete cube finite element model under compression. During the trial FEM analysis, parameters including; the mesh sizes and the loading velocities were manipulated one at a time in order to obtain the correct simulation parameter combination for the uniaxial compression of CWLB cube FEM model in Abaqus CAE. The rationale for the mesh refinement was based on the importance of appropriate selection of adequate mesh sizes and element type for correct simulation of a system behaviour in a reasonable computational time (Haghinejad and Nematzadeh, 2016). The 50 mm cube model geometry was utilized for the trial simulation since the value of its crushing load was already available from laboratory data and this gave room for validating the findings from the various trial simulation runs as well as identifying the most correct simulation parameter combination for determining the crushing load. Thus, the mesh refinement and loading velocity variations were performed during the trial simulation until the solution that mostly replicate crushing load with least percentage (%) difference compared to that obtained from the laboratory experimentation was reached. Considering the simplicity of the modelling simulation being conducted on CWLB and the use of basic CWLB material characteristics, the parameters evaluated were restricted to the highest compressive load capacity and the load versus displacement response at the moving end. The deformed shape of the cube was not evaluated in this study since the accuracy of such evaluation can only be guaranteed when the comprehensive material constitutive model (of a physical problem) are included in the analysis to predict a material inelastic behaviour and damage parameters (Goh *et al.*, 2014; Chaudhari and Chakrabarti, 2012; Abaqus theory guide 6.13, 2013). The procedure and simulation parameters from the most correct solution was employed as far as practicable to simulate the crushing load for the prototype insitu hollow and solid CWLB 3D Finite Element models. This approach of judging the precision of the numerical model by comparing the results from the model against the experimental data had been successfully used in similar previous studies by; Gupta and Singh (2014), Haghinejad and Nematzadeh (2016) etc.

7.3.2 FEM of CWLB

As shown in Table 7.1, three different geometries of 3D nonlinear finite element models were developed to analyse CWLB subjected to uniaxial compression load for the purpose of determining the approximate compressive strength of its insitu representative samples including; hollow and solid geometries having similar dimension of length, width and height. Akin to the analysis procedure commonly utilized in the previous similar studies; (Haghinejad and Nematzadeh, 2016; Abaqus 6.13, 2013), the explicit dynamic analysis available in the Abaqus explicit module was employed. The basic material properties of CWLB including; elastic modulus and density, obtained from experimental results were used as input for the simulation and due to the unavailability of tensile strength properties of CWLB from laboratory experimentation, a value of Poisson ratio similar to that assumed by Haghinejad and Nematzadeh (2016) for the simulation of crushing load of foamed concrete was assumed for CWLB. The approach of using the basic material properties including the elastic modulus, density and poison ration is in alignment with the Abaqus analysis user guide, which permits the use of same for simple stress analysis such as those involving the determination of force causing displacement of a body (Abaqus 6.13, Keyword edition, 2013). The CWLB model geometries and corresponding properties that were supplied as input for the analyses are itemized in Table 7.1.

Table 7.1: CWLB model geometries and corresponding material characterization/properties supplied as input for FEM Analysis

Model Geometry	Specimen size L x W x H (mm)	core Size (mm)	Loaded Area (mm^2)	Elastic modulus (MPa)	Density Kg/m^3	Poisson ratio
Cube	50x50x50	-	2500	883.38	910.5	0.2
Hollow	440x140x215		50400	883.38	910.5	0.2
Solid	440x140x215		61600	883.38	910.5	0.2

7.3.2.1 Finite Element type, contact and Interaction, Loading and Boundary condition utilized for Simulating Uniaxial compression of CWLB

Appropriate selection of element type play a major role in success of finite element computational procedure, based on research evidence, the eight- node three dimensional deformable continuum element (C3D8) are regarded as capable of producing accuracy and efficient computational time (Gupta and Singh, 2014). Thus, in all the geometry models investigated, CWLB was modelled with a three dimensional deformable eight–node continuum element (C3D8R) and discrete rigid bodies with shell planar features were used to represent the load cell at the top and the support at the bottom of the cube model.

General contact with surface to surface discretization was defined for the interaction between the lower plate and the C3D8R cube model and a tie constraint was defined to prevent the movement of the cube away from the lower plate. A surface to surface contact with kinematic feature was defined for the interaction between the top plate and the cube, a rigid body constraint was defined for the top plate to prevent the penetration of the slave surface (C3D8R cube model surface) into the master surface (top plate surface) during the crushing analysis step.

In the simulation of uniaxial compression of a finite element model in Abaqus explicit, the crushing of the finite element model in the load module can either be simulated through the application of velocity type displacement rotation in the initial analysis step using the predefined field with the prescription of a downward movement of the top plate boundary condition in the same step, or through the prescription of a displacement boundary condition in the created crush analysis step with a definition of the amplitude and frequency of the displacement. A lot of researchers including (Goh *et al.*, 2014; Abaqus benchmark guide 6.13, 2013) have successfully implemented either of these approaches for simulation of uniaxial compression of different kinds of model geometry. In the case of CWLB under study, the former approach was employed as it appears to be most suitable in terms of the accuracy of the crushing load predicted, therefore a velocity type constant displacement was applied at the rigid body on top until the C3D8R CWLB model was crushed. Also, a symmetry and encastre boundary condition was applied to fix the lower plate from moving in any direction during the crushing process.

7.3.2.2 Simulation of compression of C3D8R CWLB cube Model geometry

In order to model the compression of the CWLB C3D8R cube, basically the C3D8R cube was assembled between two rigid plates and the top plate was pushed downward at a constant velocity for a time period of 50 milliseconds. The cube was crushed into a depth lower than its original depth. (Fig. 7.1) shows the original configuration of the cube placed between the two rigid bodies in the global coordinate. The approach of crushing the cube between two rigid bodies is similar to that employed by Goh *et al*. (2014) for the simulation of the compressive load of a foamed concrete cube and that employed by Abaqus 6.13 benchmark guide (2013a) and Peech *et al.* (1977)) for the crushing of pipe subjected to compressive load. Also, the approach of pushing down the top plate at a constant velocity to crush the cube is similar to that employed by Abaqus 6.13 benchmark guide (2013b) for the compression of cylindrical shell subjected to compressive load.

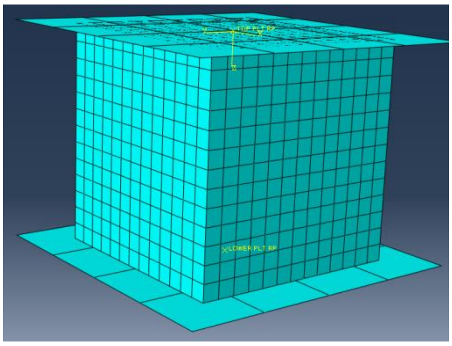


Fig. 7.1:CWLB C3D8R cube assembled between two rigid plates

7.3.2.3 Simulation of compression of C3D8R CWLB solid and hollow model geometries

As mentioned earlier in previous section of this chapter, the same approach employed for the simulation of the compression of the C3D8R cube model geometry was applied to simulate the compression of the C3D8R solid and the hollow block model geometries with regards to the property, assembly, contact interaction, analysis step and loading velocity, and analysis time period. However considering that elements and nodes are generated based on the geometry of an FEM, the meshing sizes applied to the geometries differ but similar element type and similar numbers of elements were generated as much as applicable. The meshing details showing the discretization for each of the model geometries are presented in Appendix 3. The approximate crushing load for each of the solid and hollow model geometries were investigated by using the simulation parameter combinations for C3D8R-12 which is the simulation run that produced the most correct solution for the Cube model. Based on the principle of strain and deformation in solid mechanics, the strain of solid samples made of identical material is independent of the size of the sample, since it measures the changes in the length along a particular direction with respect to the original length (Lubliner and Papadopoulos, 2014). Thus, the percentage deformation (relative to the original height) at which the C3D8R cube model geometry failed was noted, as it may represent a percentage deformation benchmark for identifying the approximate crushing load of the insitu CWLB model samples.

7.4 FINDINGS FROM SIMULATION MODELLING OF CWLB

Table 7.2 shows the several trial analyses conducted on the CWLB Cube model to obtain the correct parameter settings for accurate simulation of its compressive load. Different magnitudes of loading velocities and mesh sizes were evaluated to identify their influence on the simulation process and on the predicted compressive load of the model.

7.4.1 Effect of Meshes

The effect of mesh refinement was investigated by applying varying mesh sizes, 3, 4, 5, and 6 on the C3D8R while the applied velocity was held constant. It was observed that the number of elements (i.e. mesh density) applied on the 50mmx50mmx50mm C3D8R reduces as the mesh size increases (see Table 7.2).

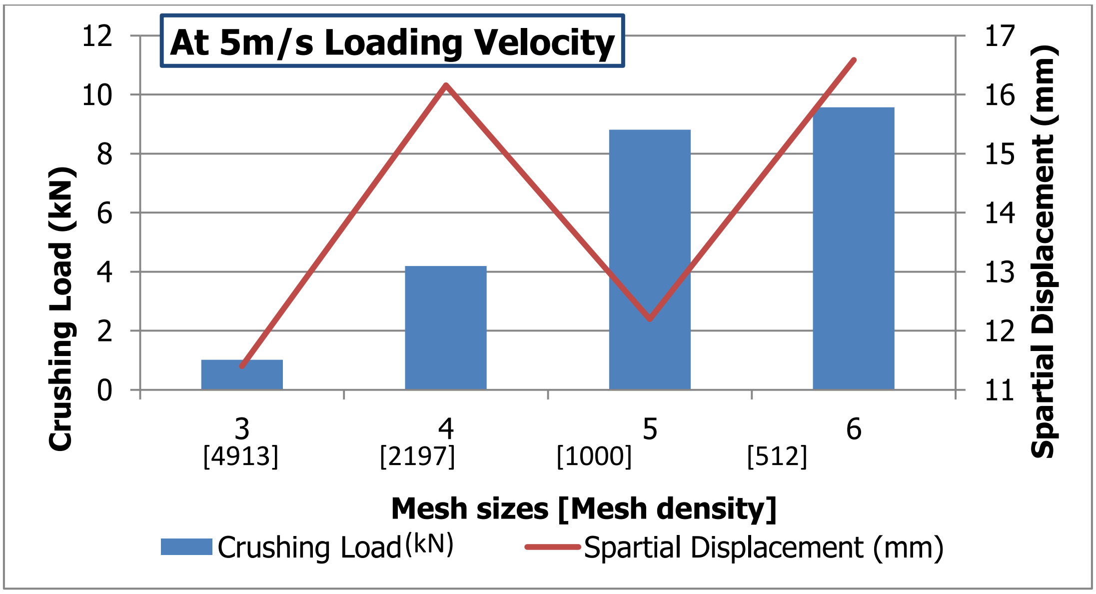


Fig. 7.2a Effect of mesh refinement on the predicted crushing load and corresponding deformation of CWLB C3D8R Cube

Also, as shown in Fig. 7.2a, when different mesh sizes were applied, it was observed that the crushing load increases as the mesh sizes increases (i.e. as the mesh density reduces) (see Table 7.2) while the magnitude of deformation caused on the cube model increases in an irregular pattern.

Table 7.2: Trial Finite element Analysis conducted on CWLB C3D8R cube model

Finite Element Modelling Simulation Runs ID	Mesh refinement			Loading Velocity (m/s)	Deformation (mm)	Crushing Load (N)	Percentage difference from experimental data (%)
	Mesh sizes	Number of Elements	Number of nodes				
C3D8R 1	6	512	729	5	16.59	9570.05	-41.26
C3D8R 2	5	1000	1331	5	12.20	8816.31	-30.13
C3D8R 3	5	1000	1331	4.780	11.68	7343.1	-8.39
C3D8R 4	5	1000	1331	4.768	11.70	2789.48	58.83
C3D8R 5	5	1000	1331	4.766	11.61	5473.15	19.22
C3D8R 6	5	1000	1331	4.770	11.62	7719.18	-13.94
C3D8R 7	5	1000	1331	4.500	11.30	2708.92	60.01
C3D8R 8	4	2197	2744	5.00	16.16	4196.39	38.06
C3D8R 9	4	2197	2744	5.200	16.7	11355.1	-67.6
C3D8R 10	4	2197	2744	5.150	16.60	7145.38	-5.47
C3D8R 11	4	2197	2744	5.145	16.57	9253.7	-36.58
C3D8R 12	4	2197	2744	5.141	16.54	6750.34	0.36
C3D8R 13	4	2197	2744	5.140	16.54	6128.42	9.54
C3D8R 14	4	2197	2744	5.100	16.50	5655.08	16.53
C3D8R 15	3	4913	5832	5.00	11.40	1021.63	84.92
Experimental data	**-**	**-**	**-**	**-**	**-**	**6775.00**	**-**

7.4.2 Effect of Loading Velocity

The effect of displacement was investigated by applying different magnitudes of velocity to push the top plate downward to crush the cube block model while the mesh size was held constant. As shown in Table 7.2 it was observed that each magnitude of loading velocity applied usually produces a particular magnitude of displacement of the nodes in the model depending on the response of the cube stiffness and the cube model usually get crushed into a depth lower than its original depth. As shown in Fig. 7.2b, at varying loading velocity and constant mesh density (1000 number of elements), both the predicted crushing load and the deformation caused on the cube model increases in an irregular manner as the velocity increases. However, at varying loading velocity and constant mesh density of 2197 number of elements, the predicted crushing load and the deformation caused on the cube increases consistently as the velocity increases (Fig. 7.2c). The trend of the predicted load- displacement curve indicates that crushing load generated was apparently influenced by the response of the cube model. The observed consistency is an indication of the adequacy of mesh size 4mm (mesh density 2197) to produce more accurate prediction of the compressive load carrying capacity of CWLB cube.

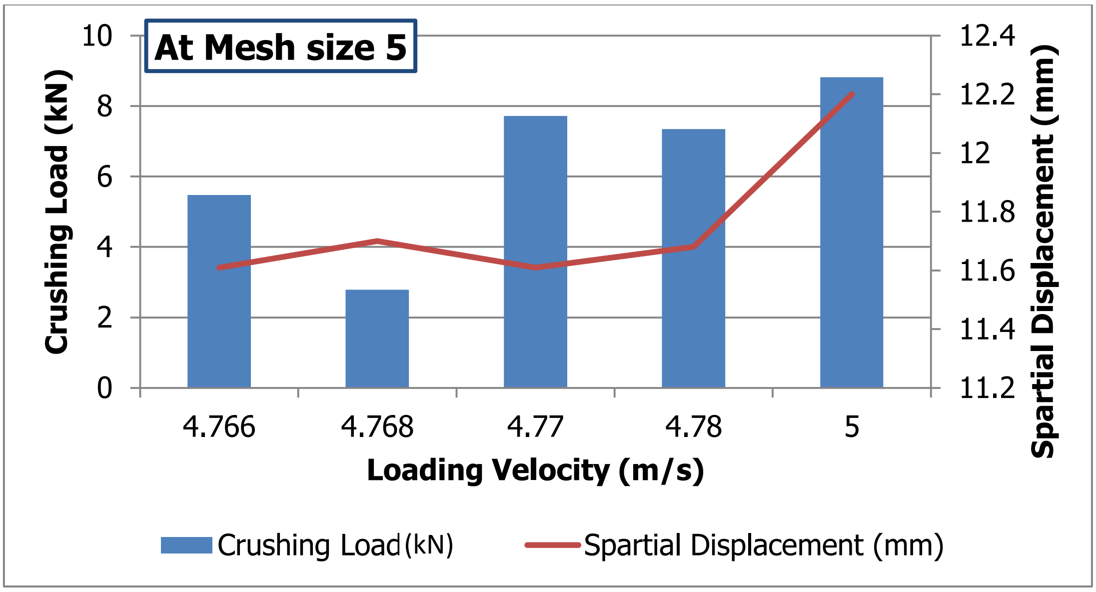


Fig. 7.2b: Effect of varying loading velocity on the predicted crushing load and corresponding deformation of CWLB C3D8R Cube at constant mesh size 5mm

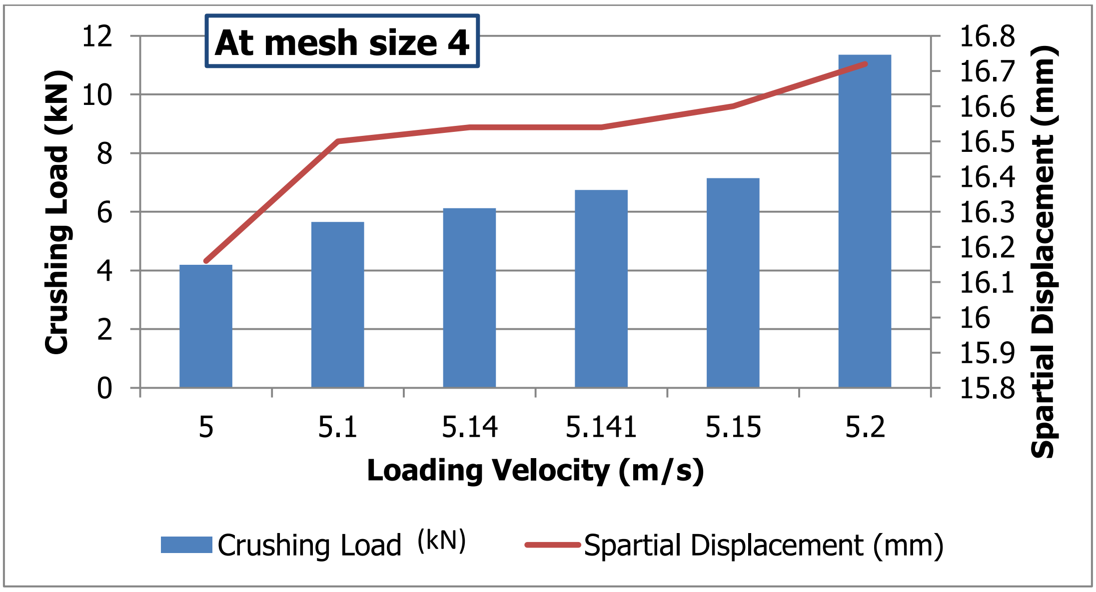


Fig. 7.2c: Effect of varying loading velocity on the predicted crushing load and corresponding deformation of CWLB C3D8R Cube at constant mesh size 4mm

7.4.3 Correct FEM solution for predicting the Compressive load of CWLB

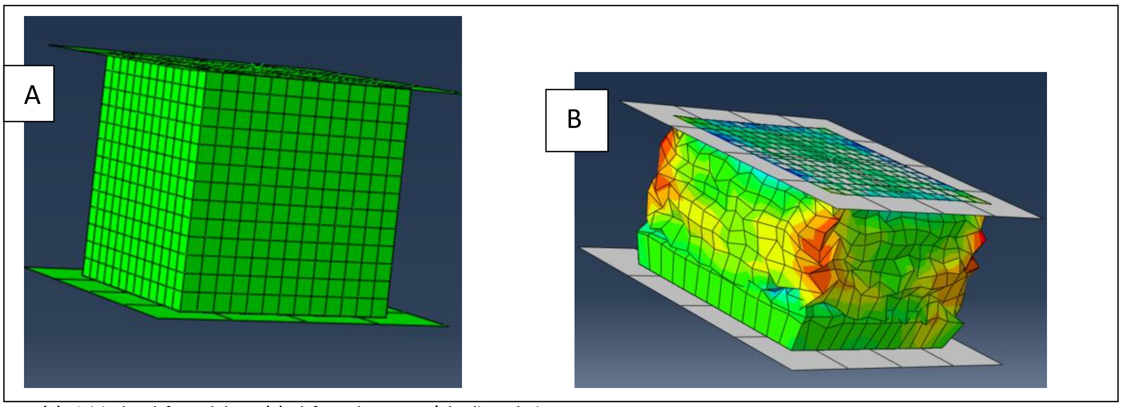
The parameter setting used for the FEM simulation run C3D8R-12 represents the most correct solution for the uniaxial compression of the 50mm x 50mm x 50mm

C3D8R CWLB finite element model as it produces the most similar crushing load compared to that obtained from laboratory experimentation. A crushing load of 6.750 kN was predicted by the C3D8R-12 compared to the 6.775 kN obtained from experimental data. Comparatively, a very small percentage difference of 0.36% was observed between the crushing load obtained from C3D8R-12 and that obtained from experimental data. Base on the simulation parameter combination for C3D8R-12 (Table 7.3a), it is apparent that the most correct solution for crushing of CWLB was obtained at; a loading velocity of 5.141 m/s, and at a mesh size 4 mm having a mesh density of 2197. The deformation of 16.54 mm at point of failure of the cube model represents 33.08% downward percentage displacement relative to the original height of the cube and a strain of 0.6692. Other parameter combinations including; number of element, number of nodes and element types for the top and lower rigid plates are presented in Appendix 3.

Fig. 7.3 shows the original un-deformed shape and the deformed shape of the cube at 16.54 mm deformation. Fig. 7.4 shows the predicted crushing load–deformation curve obtained from the most correct solution for the cube model (i.e. simulation run C3D8R-12).

Table 7.3a: The Most Correct Simulation Parameter Combination for CWLB C3D8R Cube Block model and its predicted compressive response versus Experimental compressive response

	Simulation parameter combination			Predicted compressive response			
	Mesh size	No of elements (mesh density)	Loading velocity (m/s)	Deformation (mm)	Percentage downward deformation relative to Original height of Cube model (%)	Crushing load (kN)	Estimated Compressive strength (MPa)
C3D8R-12	4	2197	5.141	16.54	33.08	6.750	2.70
Experimental data	-	-	-	-		6.775	2.71



Note: (A)= Original Undeformed shape, (B)= deformed at 5.141m/s loading velocity

Fig 7.3: Original Un-deformed and Deformed shape of CWLB C3D8R Cube

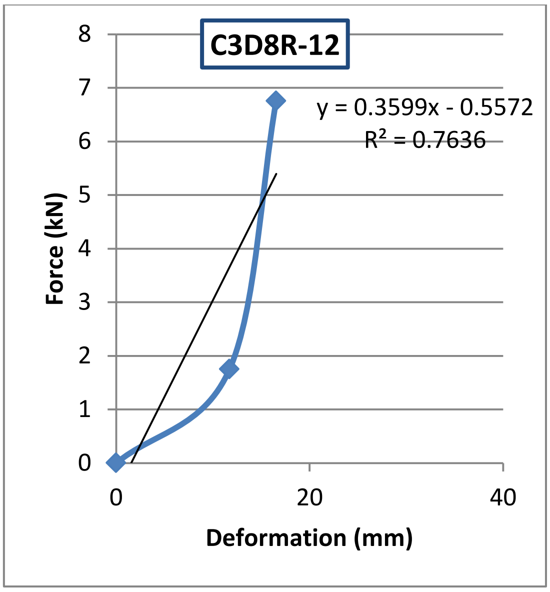


Fig 7.4: Predicted Crushing Load–Deformation Curve for C3D8R cube Model

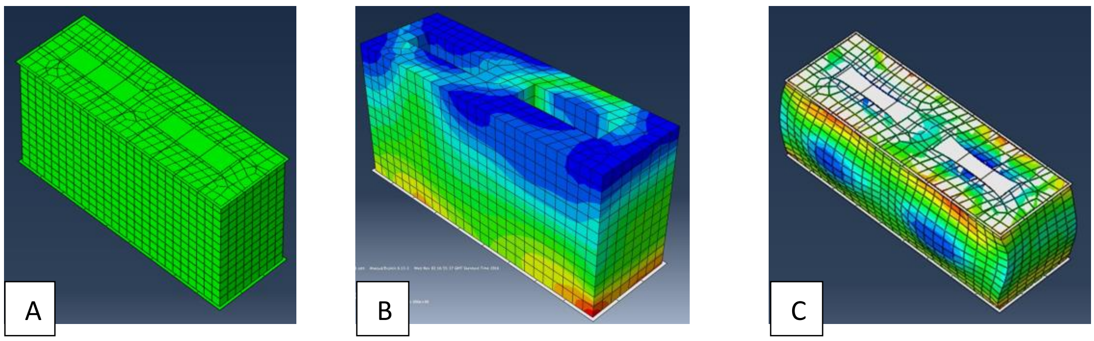
7.4.4 Simulated Compressive Load Of Hollow Insitu Prototype Sample of CWLB

As shown in Table 7.4, the predicted approximate crushing load of hollow CWLB model range between 79.49 kN and 67.81 kN which represents the respective crushing load generated at 33% and 30% displacement of the hollow block relative to its original depth of 215 mm. The approximate compressive strength for the hollow bock model estimated based on the predicted crushing load ranges between 1.58 MPa and 1.35 MPa respectively. The hollow block model remained un-deformed when it was compressed at the loading velocity of 5.141 m/s (which is the exact loading velocity at which the cube was crushed) and no apparent crushing was observed until it was compressed at 11 times the loading velocity that crushed the cube model (see section 7.5.3 for justification of this occurrence).

Fig. 7.5 shows the original un-deformed shape, the apparent un-deformed shape at 5.141 m/s loading velocity and the deformed shape of the hollow block model at 56.551m/s loading velocity (i.e.11x5.141 m/s). Fig. 7.6 shows the predicted crushing load–deformation curve obtained at 33% and 30% deformation relative to the original height of the hollow block model.

Table 7.4: Simulation parameter combination and corresponding predicted compressive response of CWLB C3D8R Hollow block model

FEM ID	FEM Analysis parameter				Predicted compressive response			
	Number of elements (mesh density)	**Number of nodes**	**Loading velocity (m/s)**	**Loaded area (mm^2)**	**Deformation**	**Percentage Downward Deformation relative to Original depth (%)**	**Crushing Load (kN)**	**Approximate Compressive strength (MPa)**
Hollow-C3D8R-1	2262	3178	56.551	50400	70.065	33%	79.4910	1.58
Hollow-C3D8R-2	2262	3178	61.692	50400	68.617	30%	67.8117	1.35



Note: (A)= Original Un-deformed, (B)= Un-deformed at 5.141m/s C3D8R cube loading velocity and (C)= Deformed shape at 11 times C3D8R Cube loading velocity

Fig 7.5: Original un-deformed shape and deformed shape of CWLB C3D8R Hollow block Model

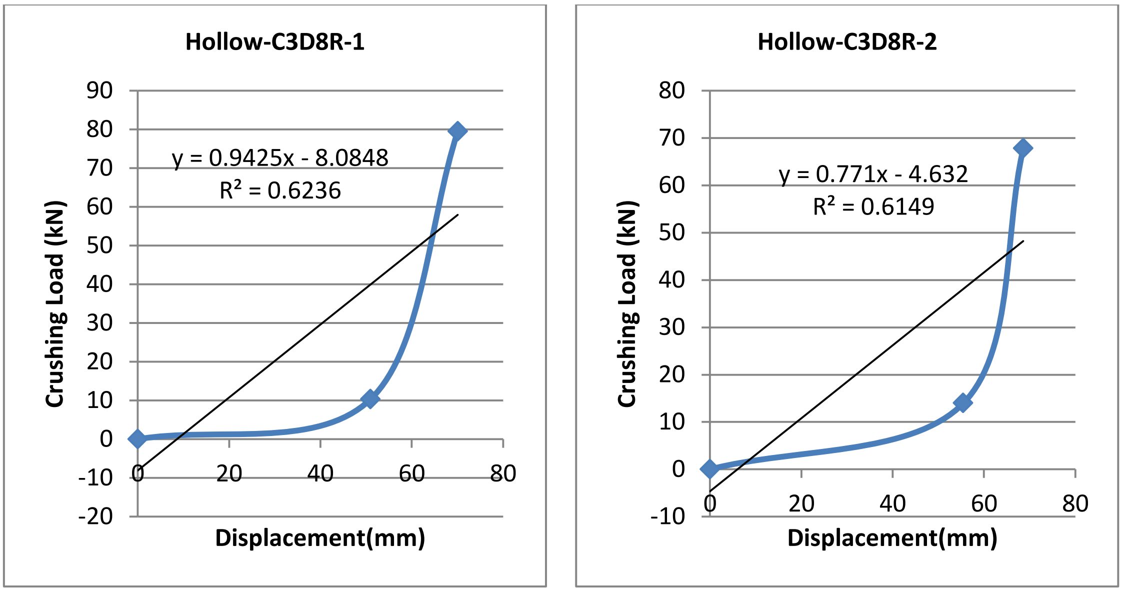


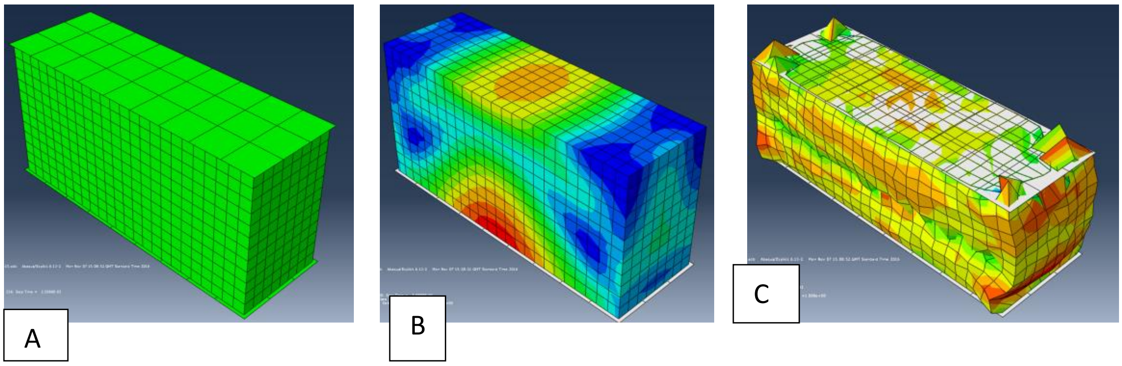
Fig 7.6 Predicted crushing load–deformation curve obtained at 33% (Hollow-C3D8R-1) and (Hollow-C3D8R-2) 30% deformation relative to the original height of Solid block

7.4.5 Simulated compressive load of solid insitu prototype sample of CWLB

As shown in Table 7.5, the predicted approximate crushing load of CWLB C3D8R solid block model range between 146.45 kN and 74.97 kN which represent the respective crushing load generated at 30% and 40% displacement of the solid block relative to its original depth. The approximate compressive strength for the solid bock model estimated based on the predicted crushing loads ranges between 2.38 MPa and 1.21 MPa respectively. The solid block model remained un-deformed when it was compressed at the loading velocity of 5.141 m/s and no apparent crushing was observe until it was compressed at 15 times the loading velocity that crushed the cube model (see section 7.5.3 for justification of this occurrence). Fig. 7.7 shows the original un-deformed shape, the apparent un-deformed shape at 5.141 m/s loading velocity and the deformed shape of the solid block model at 77.115 m/s loading velocity (i.e.15x5.141 m/s). Fig. 7.8 shows the predicted crushing load–deformation curve obtained at 30% and 40% deformation relative to the original height of the solid block model.

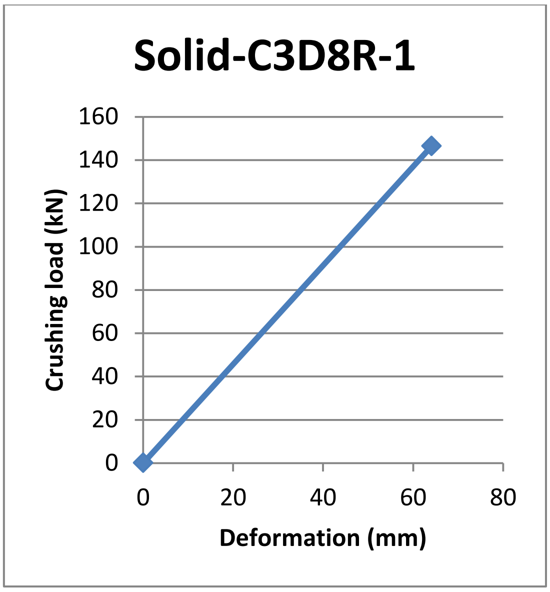
Table 7.5: Simulation parameter combination and corresponding predicted compressive response of CWLB C3D8R Solid block model

FEM ID	FEM Analysis parameter				Predicted compressive response			Approximate Compressive strength (MPa)
	No of elements (mesh density)	No of nodes	Loading velocity (m/s)	Loaded area (mm^2)	Deformation	Deformation relative to Original depth (%)	Crushing Load (kN)	
Solid-C3D8R-1	2304	2925	77.115	61600	64.127	30%	146.446	2.38
Solid-C3D8R-2	2304	2925	82.256	61600	86.917	40%	74.966	1.21



Note: (A)= Original Undeformed, (B)= Undeformed at 5.141m/s C3D8R cube loading velocity and (C)= Deformed shape at 15 times C3D8R Cube loading velocity

Fig 7.7: Original undeformed shape and deformed shape of CWLB C3D8R Solid block Model



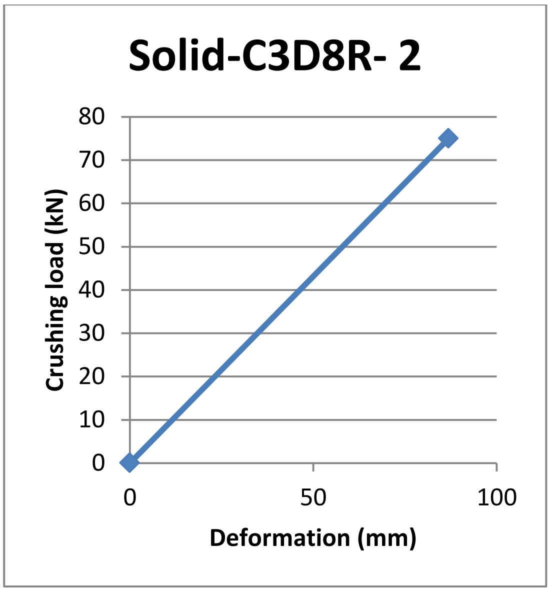


Fig 7.8: Predicted Crushing load–deformation curve obtained at respective 30% (Solid-C3D8R-1) and 40% (Solid-C3D8R-2) deformation relative to the original height of Solid block

7.5 DISCUSSION OF FINDINGS

This section presents the engineering judgements formulated based on the findings presented in section 7.4 of this Chapter.

7.5.1 Accuracy Of Finite Element Simulation Of Uniaxial Compression of CWLB

Based on related similar studies from the literature, the accuracy of an FEM stress analysis can be verified through a mesh convergence study or through the agreement of the FEM result with that of the experimentally obtained data (Goh *et al.*, 2016; Abaqus 6.13 Benchmark guide, 2013a; Onsalung *et al.*, 2014). In the case of the latter verification approach, the percentage difference between the FEM predicted crushing load and that of the experimentally obtained crushing load usually determines the level of the accuracy of the analysis. Based on the findings from this study, the crushing load of 6.75 kN predicted by the simulation run

C3D8R-12 has a small percentage difference of 0.36% compared to the 6.775 kN crushing load obtained for the same size of specimen in the laboratory. This indicates that the analysis procedure employed and the basic material characteristic (density, elastic modulus, poison ratio and specimen geometry) supplied as input for the simulation of the compression process of CWLB were capable of predicting the crushing load as well as compressive strength with 99.64% accuracy.

7.5.2 Finite Element Meshing of CWLB

In finite element modelling, variation in mesh sizes produces varied number of elements (also known as mesh density) for same model geometry (Aktay *et al.*, 2006). Thus the observed variation in mesh density of CWLB C3D8R cube model for different mesh size definition can be regarded to be in agreement with the principle of finite element meshing and model geometry discretization. The level of accuracy of finite element analysis model depends largely on the finite element mesh employed for the discretization of a model geometry (COMSOL, 2016) because it is the main parameter that determines the size of elements from which the necessary governing equations are developed (Abaqus 6.13 keyword edition, 2013). Based on literatures, the computed solution of Finite Element Analysis usually approach true solution as the mesh is refined and as the elements get smaller and smaller (COMSOL, 2016). This explains the irregularity of both the predicted crushing load and the axial deformation displayed by the cube model meshed with coarser mesh size 5mm and 6mm (Fig. 7.2a and 7.2b) in terms of intermittent overestimation and underestimation of the compressive response of the cube at varying and similar loading velocities. The consistency in the predicted crushing load and axial deformation recorded for the cube model with mesh size 4 mm at varying and similar loading velocity may thus be regarded as an indication of its suitability for the CWLB cube model.

7.5.3 Justification for the Higher Loading Velocity Predicted for Crushing of the Insitu Solid and Hollow Model Samples of CWLB

As can be appreciated from Tables; 7.2, 7.4 and 7.5, the loading velocity predicted for crushing the hollow and the solid CWLB model sample was 11 times and 15 times of the magnitude of loading velocity predicted for crushing of the cube model sample. This higher loading velocity requirement displayed by the insitu (solid and hollow) CWLB model samples with larger cross sectional area is expected and the reasons for this occurrence can be explained based on the principles of solid mechanics and Newtonian mechanics. Newton's law of motion made it quite clear that the displacement of a body per unit time is caused by a force; the force causing the displacement is usually related to the mass and the velocity of the moving object. Higher velocity is required to cause the displacement of an object having higher mass and higher velocity is usually caused by higher moving forces (Kelly, 2013; Lubliner and Papadopoulos, 2014). Also, in solid mechanics, the force required to break or crush a given sample of a material is proportional to its cross section area (Lubliner and Papadopoulos, 2014), in other words, the force required to compress given samples of solid body made with identical material will vary depending on the cross sectional area of each of the samples. Samples with larger cross sectional areas will require larger compressive forces while those with smaller cross sectional areas will require otherwise. Thus, the higher loading velocities predicted for crushing of the CWLB insitu solid and hollow samples compared to that of the small cubic laboratory sample may be attributed to the variation in the; bulk mass, cross sectional area and the height to width ratio of the model samples.

7.5.4 Approximate Compressive Load Carrying Capacity and Compressive Strength of CWLB Insitu Solid and Hollow Samples

The results presented in Tables 7.4 and 7.5 shows that solid and hollow CWLB block models respectively failed at larger magnitude of crushing load 146.45 kN and 79.49 kN compared to the 6.750 kN crushing load predicted for the cube model. However, the corresponding compressive strength values of 2.38 MPa and 1.58 MPa estimated from the predicted respective crushing load of the solid and hollow block are 12% and 42% less than the 2.70 MPa compressive strength estimated for the cube model.

At a given material characteristics, the magnitude of the loaded cross sectional area of a specimen subjected to compressive load determines the magnitude of the crushing load that it can sustain, though higher magnitude of crushing load does not necessarily indicate higher compressive strength since compressive strength is the ratio of applied load at failure to the cross sectional loaded area of the specimen (Lubliner and Papadopoulos, 2014). Bulky or larger specimens tend to be weaker compared to compact or smaller specimens (Galileo 1638 cited in Bazant, 1999). This explains the reason why the approximate crushing load predicted for the larger size block models (i.e. solid block geometry with loaded area 61600 mm^2 and the hollow block geometry with loaded area 50400 mm^2) are higher than that predicted for the cube block model with loaded area 2500 mm^2

The lower compressive strength predicted for the larger CWLB block geometry may be attributed to the effect of height to width ratio on the compressive strength of a material. This finding may be an indication that CWLB may exhibit higher compressive strength for geometry with low height to width ratio compared to geometries with high height to width ratio and it is in agreement with the evidence from the literature which suggests that the strength of quasi-brittle material decreases with increase in specimen size (Ghaemmaghami and Ghaemian,2006).

The compressive strength of 2.38 and 1.58 MPa predicted for the solid and hollow CWLB blocks was recorded at 30% and 33% percentage deformation relative to their original height of 215 mm. This is in close proximity to the 33.08% deformation at which the compressive strength of the cube model sample was recorded. This is in line with basic principle of strain and deformation in which solid samples made with similar materials usually attain their compressive stress at similar (or slightly different) strain regardless of the difference in the size (Lubliner and Papadopoulos, 2014).

The approximate compressive strength of 2.38 and 1.58 MPa predicted for the solid and hollow CWLB blocks maximally satisfies the compressive strength requirement for non-load bearing lightweight block as specified by BS EN 771-4 (2011) (and others including Nigeria building code, Ghana building code and New Zealand building code)

7.6 INFERENCES FROM SIMULATION MODELLING OF CWLB

The non-linear finite element analysis of the compression process of CWLB laboratory and insitu representative samples has been carried out in this study using Abaqus CAE version 6.13 (2013). The explicit dynamic analysis method available in Abaqus standard explicit was employed for the analysis due to its ability to provide a more computational (CPU) cost-effective solution to the large non-linear system of equation generated during the simulation (Abaqus 6.13 online Documentation, 2013). The CWLB model geometries investigated includes: a 50mm x 50mm x 50mm laboratory cube specimen, a 440mm x 140mm x 215mm insitu solid block sample and a 440mm x 140mm x 215mm insitu hollow block sample with blind extruded core size 140mm by 40mm. Being a simple modelling simulation, performed to only determine the approximate load carrying capacity of CWLB insitu prototype samples, the basic CWLB material characteristics (including; elastic modulus, density and an assumed poisson ratio) were supplied as input to simulate its compressive response. The parameters evaluated from the analysis include the highest compressive load capacity and the load versus displacement response at the CWLB models. It should be noted that this analysis was performed with an understanding that findings of finite element modelling simulation represent approximate solution to a physical problem therefore the findings are believed to represent an approximate solution that can give an idea of load carrying capacity of CWLB insitu representative sample in real life application. The following conclusions were made based on the findings from this study.

The Nonlinear FEM simulated compression process for CWLB is capable of predicting its crushing load as well as compressive strength with 99.64% accuracy.

Mesh size 4 mm with corresponding mesh density depending on the model geometry produces the optimum discretization for CWLB finite element models.

CWLB with geometry having a small height to width ratio has the tendency to display higher compressive strength compare to those with higher height to width ratio

The C3D8R CWLB cube model displayed 2.70 MPa compressive strength which represents 99.64% of the 2.71 Mpa compressive strength obtained from the laboratory.

The C3D8R CWLB solid and hollow models displayed respective compressive strength of 2.38 MPa and 1.58 MPa at 15 times and 11 times the loading velocity of the cube model.

The approximate compressive strength of 2.38 MPa and 1.58 MPa predicted for the solid and hollow CWLB insitu model samples are 12% and 42% less than the 2.70 MPa compressive strength estimated for the cube model sample.

The failure of the C3D8R cube, solid and hollow geometries sequentially occurred at 33.08%, 30% and 33% percentage deformation relative to their respective original heights.

The compressive strength of 2.38 MPa and 1.58 MPa predicted for the solid and hollow CWLB blocks at 30% and 33% percentage deformation relative to their original height of 215 mm.

CWLB solid and hollow insitu samples can be regarded as suitable for application as lightweight non load bearing block in building construction base on their predicted approximate compressive strength which maximally satisfies the 1.5 MPa minimum compressive strength recommended by BS EN 771-4:2011 for lightweight non load bearing blocks

7.7 SUMMARY OF CHAPTER

This chapter presented the details and findings from the numerical simulation modelling performed to investigate the approximated compressive strength of CWLB insitu solid and hollow samples. The study represents the fifth objective of the research. The rationale for embarking on this study, the methods adopted, findings and the discussions are presented in section 8.3, 8.4, 8.5 and 8.6 of this Chapter respectively.

The next chapter (i.e. Chapter 8) will present the summary along with the contribution of this research to the body of knowledge, as well as the conclusions, and recommendations for future investigation.

CHAPTER EIGHT: SUMMARY, CONCLUSION AND RECOMMENDATIONS

8.1 SUMMARY OF RESEARCH PROGRAMME

The research programme has investigated the applicability of recycled waste paper as lightweight building materials through the development of a novel cement-less wastepaper based lightweight block (CWLB).

The experimental programme comprised of two major stages including the preliminary laboratory experimentation (i.e. stage 1) and the main experimentation (i.e. Stage 2). The experimental investigations conducted in stage 1 addressed the second objective of the research while the investigations conducted in each of the four phases comprised in stage 2 addressed the 3rd, 4th 5th and 6th objective of the research respectively.

During the stage 1, the processing of wastepaper into wastepaper aggregate (WPA), characterisation of constituent materials and the development of mixture proportioning process for CWLB were carried out. The suitable mixture proportioning process for the CWLB was developed through the application of trial mix batch approach which gave room for the assessment of relevant processing parameters (including mixing method, curing method, trial mix composition, molding method, specimen sizes etc.) and the subsequent making of evidenced informed decisions for same. At the end of this stage, a suitable manufacturing technology for CWLB was obtained and five trial mixes were arrived at.

The stage 2 of the research comprises of 4 phases of experimentations. The first phase investigated the behaviour of CWLB at varying controlled instances of processing parameters through the study of factors that influence its compressive strength. The main reasons being to identify factors required to maximise its compressive strength. The second phase of the experimentation investigated the optimum mix composition of CWLB by incorporating the crucial factors identified from phase 1 to determine the optimum combination of processing parameters. The third phase of the experimentation investigated the engineering properties of CWLB (including; compressive strength, density, UPV, capillary water absorption, elastic modulus, and thermal conductivity). The forth phase simulated the compressive load of a finite element modelled prototype of typical representative samples of CWLB, through the use of Abaqus CAE modelling and simulation software.

At the end of this research it was apparent that the results obtained from each of the stages and phases of experimentation conducted in this research have efficiently provided answers to the research questions set at the commencement of this study. Being a novel building material, the findings and outcomes from each of the experimentations conducted in the process of developing CWLB forms the contribution of this research to the body of knowledge (see Table 8.1).

Table 8.1: Brief Summary of contribution to Knowledge from research experimentation

Experimental Stage No	Stage ID	Contribution to knowledge	Thesis Chapter
1	Preliminary Lab Experimentation	1) Development of wastepaper aggregate (WPA) – which is a granular lightweight aggregate that can be applied in a conventional manner like other manufactured aggregate. 2) Development and design of mixture proportioning process for CWLB- which is a manufacturing technology that can be executed in a manner similar to that available for conventional masonry block.	Four
2	Main experimentation		
	Phase 1: Study of salient parameters	Determination of the behaviour of CWLB which provide an understanding of the factors that can be used to manipulate its properties.	Five
	Phase 2: Optimization	Determination of optimum mix composition of CWLB which provide knowledge of the optimum processing parameter combination and the rank of each of their effects on its compressive strength.	
	Phase 3: Engineering properties	Determination of the engineering properties of CWLB including: Compressive strength, UPV, Elastic modulus, Density, Capillary water absorption, Thermal conductivity, the knowledge of which provides evidence of its suitability for non-load bearing application in building construction.	Six
	Phase 4: Simulation modelling of compressive load of CWLB Field representative sample	1) Development of finite element analysis procedure for simulation of compressive response of CWLB, which can be applied to simulate same for related building materials. 2) Determination of the approximate compressive load carrying capability (i.e. compressive strength) of representative insitu solid and hollow finite element model samples of CWLB.	Seven

8.2 CONCLUSIONS

The conclusions drawn from each of the stages and sub phases of main experimentations conducted this research programme are highlighted below:

- The waste additive (i.e. waste lactose) was effective as binder for the production of CWLB from constituent materials including; WPA, sand, admixture (stoneware clay) and water.
- CWLB fresh mixture is ash in colour and exhibits fibrous cohesive texture and displays characteristics that are similar to that of densified biomass during compaction
- The compressive strength of CWLB is affected by parameters including; curing age, curing temperature, WPA particle size, water content, compacting force, binder content and curing orientation but at different intensity.
- Water content has the most substantial effect on the compressive strength of CWLB. The compressive strength of specimen containing 15% water content was 219% higher than those containing 75% water content.
- The compressive strength of CWLB can be manipulated by varying its water/binder ratio, WPA/sand ratio along with the compacting forces.
- Water/binder ratio has the most significant effect on the compressive strength of CWLB
- The optimal processing parameter combination for CWLB includes: 2.5 WPA/Sand ratio, 0.75 Water/Binder ratio, and 3.5 metric ton Compacting force (5% admixture (measured by wt. of WPA), WPA particle passing 3.35

mm BS sieve, 28 days curing duration, open air/ambient curing temperature).

- The optimum mixture composition of CWLB which contains 62.5% WPA, 25% Sand and 12.5% waste additive (binder) indicates that CWLB possess 75% waste content and this characteristic makes CWLB a highly eco-friendly block in terms of its potential to contribute to natural resources conservation.
- At optimum mix composition, CWLB possess an average compressive strength of 2.71 MPa (n=3) and a corresponding average density of 901.5 kg/m^3 at 28 days curing age.
- The average compressive strength of the optimized weaker mixes of CWLB range between 2.59 MPa and 2.39 MPa and the corresponding average densities ranged between 914 kg/m^3 - 881.7 kg/m^3.
- At optimum mix composition, CWLB exhibits an average UPV value of 989.9 m/s and a strong agreement exist between this value and the optimum compressive strength of CWLB with a positive correlation coefficient of 0.9773.
- At optimum mix composition, CWLB exhibits an average coefficient of capillary water absorption of 0.0026 $g/(m^2xs^{0.5})$ (n=3).
- The thermal conductivity of CWLB range from 0.19 W/m.K to 0.52 W/m.K indicating its good insulating property.

- At optimum mix composition, CWLB exhibits an estimated elastic modulus of 883.38 MPa. The estimated elastic modulus of CWLB's weaker mixes rage from 789.88 MPa to 710.19 MPa
- CWLB exhibits potential for use in higher strength application with minimal stabilization, the compressive strength of optimal CWLB is equivalent to the compressive strength of its 2% and 4% cement stabilized version.
- The compressive strength of SWLB at 2, 4, 6, 8 and 10% cement inclusion are 2.70 MPa, 2.76 MPa, 2.82 MPa, 3.00 MPa, and 3.48 MPa respectively.
- The 3.00 MPa and 3.48 MPa average compressive strength respectively displayed by SWLB at 8 and 10% cement inclusion are 7% and 24% higher than the 2.8 Mpa specified by BSEN 6073-1:1981 for aggregate concrete block.
- The 3.48 MPa average compressive strength displayed by SWLB at 10% cement inclusion is 20% higher than the 2.9 MPa being commonly declared for commercially available AAC block in the UK construction industry.
- The C3D8R CWLB solid and hollow models displayed respective compressive strength of 2.38 MPa and 1.58 Mpa at 15 times and 11 times the loading velocity of the cube model.
- The approximate compressive strength of 2.38 MPa and 1.58 MPa predicted for the solid and hollow CWLB insitu model samples are 12% and 42% less than the 2.70 MPa compressive strength estimated for the cube model sample.

8.3 APPLICATION OF CWLB

The importance of lightweight building material cannot be overemphasized, because it uses as a building component bring about reduction in the dead weight of a structure. It uses reduces the cost of construction, cost of foundation, and time period for construction.

The cement-less wastepaper-based lightweight block (CWLB) developed in this research can be used for various non-loadbearing/non-structural lightweight application in building construction as highlighted below:

i) CWLB can be used as lightweight block for internal partitioning in both low rise and high rise building structure.

ii) CWLB can be used for internal partitioning in building structure constructed in earthquake prone environment

iii) The SWLB developed exhibit potential for use in lightweight load bearing applications that are not exposed to the element of the weather.

iv) CWLB can be used as insulation for two leave internal wall.

v) CWLB can also be used as wall element in floating building structures commonly constructed on water bodies.

8.4 LIMITATION OF RESEARCH

1) The hydraulic press used was a manually operated one and the installed pressure gauge was an analogue display one. This indicate the possibilities of human error in the order of ±0.05 in the amount of molding pressure applied and the possibility of a slight discrepancy in the pressure reading from the analogue pressure gauge.

2) Flexural strength and tensile strength test could not be carried out on CWLB due to unavailability of relevant equipment to mold the required standard size of test specimen.

3) A typical real life representative CWLB sample could not be molded due to lack of relevant equipment.

4) The elastic modulus of CWLB was estimated using the empirical formula relating the UPV, density and elastic modulus of a solid material.

5) An approximate compressive strength was determined for CWLB insitu representative sample through the use of finite element modelling simulation in order to predict its load carrying capability in the absence of laboratory data.

6)The samples tested for determination of thermal conductivity K were not insulated, there is therefore the possibility of temperature loss at the sides of the specimen during reading.

7) The fire reaction of CWLB could not be carried out due to lack of approval from relevant authorities to conduct the test in the lab on the ground of health and safety policy of the institution of study.

8.5 RECOMMENDATIONS

In this study, wastepaper has been utilized to produce an eco-friendly block which can serve a similar purpose as the conventional blocks of the same category, however, the level of details covered in this research presents opportunities for future research to explore further properties of CWLB as well as develop building materials from other similar wastes. Therefore, the following recommendations were made:

1) Future research could investigate the application of the manufacturing technology developed for CWLB to produce other eco-friendly alternative building materials from similar solid wastes e.g. saw dust.

2) Considering that the scope of the present study was limited to the use of old newsprint wastepaper, future research could investigate the application of the manufacturing technology of CWLB for the development of same type of block from other types of wastepaper e.g. cardboard, packaging waste and office paper etc.

3) Future research could investigate the design and fabrication of customized/innovative, undemanding, cost and energy efficient manufacturing equipment for CWLB.

4) Future research could investigate the application of the developed WPA as lightweight aggregate replacement in the production of other building materials.

5) Experimental based research should be carried to validate the approximate compressive strength predicted for the solid and hollow CWLB insitu finite element model sample.

6) Future research should carry out a study of long term durability of CWLB in real life application through a non-destructive long-term study of its performance efficiency in non-load bearing application

7) Future research should investigate the applicability of the stabilized wastepaper-based lightweight block (SWLB) for lightweight structural application in building construction.

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APPENDICES

APPENDIX 1: DETAILS OF CWLB TRIAL MIXES AND DETAIL DISCUSSION OF FINDINGS FROM PRELIMINARY STUDY

APX. 1.1 DETAILS OF TRIAL MIX 1 (TM1)

A total of 15 set of mixes produced for TM1 (as shown in Table Apx. 1.1). The mixtures were prepared from varied combination of WPA, sand, and binder in ratios. WPA/Sand ratio range of 0, 0.5, 0.67,1, 2 and WPA/binder ratios in the range of 1, 0.5, and 0.33 were explored. In order to observe the ability of the binder to bind the components of the mixture together in the absence of water, the waste additive was made to serve both the purpose of binder and the water content. At 28 days curing age, TS1 displayed moderate strength (Table Apx. 1.5, see section Apx.1.5.1), which suggested that the binder was able to hold the constituent materials together, however, anomalies which include shrinkage and mold growth were observed on the specimen.

APX. 1.2 DETAILS OF TRIAL MIX 2 (TM2)

TM2 was designed as an improvement over TM1, in order to optimize the mix proportion and address the anomalies observed on TS1. At this point, water was introduced into the mixture for mixing and 5% clay was incorporated as an admixture. As shown in Table Apx. 1.2, the 36 sets of mixes produced for TM2 were designed with; percentage sand content in the range of 0%-20% by weight of WPA, percentage binder content in the range of 0% -20% by weight of WPA and Water/binder ratios in the range of 10, 12.5, 16.7, 25 and 50.

Table Apx 1.1: Details of Trial Mix 1 (TM1)

Mix No.	MIX ID	Mix proportion Paper: Sand: Binder (by wt.)	Sand content (% by wt. of WPA)	Binder content (% by wt. of WPA)	Water/Binder ratios
1	M1	1 : 0 : 1	0	100	N/A
2	M2	1 : 0.5 : 1	50	100	N/A
3	M3	1 : 1 : 1	100	100	N/A
4	M4	1 : 1.5 : 1	150	100	N/A
5	M5	1 : 2 : 1	200	100	N/A
6	M6	1 : 0 : 2	0	200	N/A
7	M7	1 : 0.5 : 2	50	200	N/A
8	M8	1 : 1 : 2	100	200	N/A
9	M9	1 : 1.5 : 2	150	200	N/A
10	M10	1 : 2 : 2	200	200	N/A
11	M11	1 : 0 : 3	0	300	N/A
12	M12	1 : 0.5 : 3	50	300	N/A
13	M13	1 : 1 : 3	100	300	N/A
14	M14	1 : 1.5 : 3	150	300	N/A
15	M15	1 : 2 : 3	200	300	N/A

APX. 1.3 DETAILS OF TRIAL MIX 3 (TM3)

TM3 was designed for the purpose of introducing the static compaction method of molding CWLB so as to replicate the real-life masonry block molding technology. As shown in Table Apx. 1.3, TM3 was made up of few efficient mix compositions (mix numbers 31-36) selected from TM2 and additional mixes with higher percentage sand content ranging from 24% -52% by weight of WPA. The latter was included to assess the effect of higher sand content on the quality of the specimen and to add weight to the specimen.

Table Apx. 1.2: Details of Trial Mix 2 (TM2)

Mix No.	Mix ID	Mix ratios [Paper : Sand : Binder]	Percentage Sand content (% by wt of WPA)	Percentage binder content (% by wt of WPA)	Water/Binder ratios	Natural Admixture (Clay) (% by wt of WPA)
1	M16	1 : 0 : 0	0	0	N/A	5
2	M17	1 : 0.04 : 0	4	0	N/A	5
3	M18	1 : 0.08 : 0	8	0	N/A	5
4	M19	1 : 0.12 : 0	12	0	N/A	5
5	M20	1 : 0.16 : 0	16	0	N/A	5
6	M21	1 : 0.20 : 0	20	0	N/A	5
7	M22	1 : 0 : 0.04	0	4	50	5
8	M23	1 : 0.04 : 0.04	4	4	50	5
9	M24	1 : 0.08 : 0.04	8	4	50	5
10	M25	1 : 0.12 : 0.04	12	4	50	5
11	M26	1 : 0.16 : 0.04	16	4	50	5
12	M27	1 : 0.2 : 0.04	20	4	50	5
13	M28	1 : 0 : 0.08	0	8	25	5
14	M29	1 : 0.04 : 0.08	4	8	25	5
15	M30	1 : 0.08 : 0.08	8	8	25	5
16	M31	1 : 0.12 : 0.08	12	8	25	5
17	M32	1 : 0.16 : 0.08	16	8	25	5
18	M33	1 : 0.20 : 0.08	20	8	25	5
19	M34	1 : 0 : 0.12	0	12	16.7	5
20	M35	1 : 0.04 : 0.12	4	12	16.7	5
21	M36	1 : 0.08 : 0.12	8	12	16.7	5
22	M37	1 : 0.12 : 0.12	12	12	16.7	5
23	M38	1 : 0.16 : 0.12	16	12	16.7	5
24	M39	1 : 0.20 : 0.12	20	12	16.7	5
25	M40	1 : 0 : 0.16	0	16	12.5	5
26	M41	1 : 0.04 : 0.16	4	16	12.5	5
27	M42	1 : 0.08 : 0.16	8	16	12.5	5
28	M43	1 : 0.12 : 0.16	12	16	12.5	5
29	M44	1 : 0.16 : 0.16	16	16	12.5	5
30	M45	1 : 0.20 : 0.16	20	16	12.5	5
31	M46	1 : 0 : 0.20	0	20	10	5
32	M47	1 : 0.04 : 0.20	4	20	10	5
33	M48	1 : 0.08 : 0.20	8	20	10	5
34	M49	1 : 0.12 : 0.20	12	20	10	5
35	M50	1 : 0.16 : 0.20	16	20	10	5
36	M51	1 : 0.20 : 0.20	20	20	10	5

Table Apx. 1.3: Details of Trial Mix 3 (TM3)

Mix No.	Mix ID	Mix Proportion [Paper: Sand: Binder]	Sand content (% by wt of WPA)	Binder content (% by wt of WPA)	Water/Binder ratios	Natural Admixture (Clay) (% by wt of WPA)
1	M46H	1:0:0.20	0	20	10	5
2	M47H	1:0.04:0.20	4	20	10	5
3	M48H	1:0.08:0.20	8	20	10	5
4	M49H	1:0.12:0.20	12	20	10	5
5	M50H	1:0.16:0.20	16	20	10	5
6	M51H	1:0.20:0.20	20	20	10	5
7	M52	1:0.24:0.20	24	20	10	5
8	M53	1:0.28:0.20	28	20	10	5
9	M54	1:0.32:0.20	32	20	10	5
10	M55	1:0.36:0.20	36	20	10	5
11	M56	1:0.40:0.20	40	20	10	5
12	M57	1:0.44:0.20	44	20	10	5
13	M58	1:0.48:0.20	48	20	10	5
14	M59	1:0.52:0.20	52	20	10	5

Note: H represent Hydraulic press- static load compaction

The mixes present in TM3 were subjected to molding using static compaction method with the aid of hydraulic press in order to improve on the tamping method employed for molding TS2 and TS1 and to replicate the mechanism of block molding in real life block production.

APX. 1.4 DETAILS OF TRIAL MIX 4 (TM4)

As presented in **Table Apx. 1.4,** TM4 was produced to assess the effect of WPA particle sizes /granulation on the quality of the specimen in terms of degree of compaction.

Table Apx. 1.4: Details of Trial Mix 4 (Mix 4)

Mix No.	MIX ID.	Mix Proportion [Paper : Sand : Binder]	Sand content (% by wt of WPA)	Binder content (% by wt of WPA)	Water/Binder ratios	Natural Admixture (Clay) (% by wt of WPA)
1	M46HF	1:0:0.20	0	20	3.75	5
2	M47HF	1:0.04:0.20	4	20	3.75	5
3	M48HF	1:0.08:0.20	8	20	3.75	5
4	M49HF	1:0.12:0.20	12	20	3.75	5
5	M50HF	1:0.16:0.20	16	20	3.75	5
6	M51HF	1:0.20:0.20	20	20	3.75	5
7	M52F	1:0.24:0.20	24	20	3.75	5
8	M53F	1:0.28:0.20	28	20	3.75	5
9	M54F	1:0.32:0.20	32	20	3.75	5
10	M55F	1:0.36:0.20	36	20	3.75	5
11	M56F	1:0.40:0.20	40	20	3.75	5
12	M57F	1:0.44:0.20	44	20	3.75	5
13	M58F	1:0.48:0.20	48	20	3.75	5
14	M59F	1:0.52:0.20	52	20	3.75	5

Note: H represent Hydraulic press- static load compaction; F represent fine WPA (i.e. WPA-type B)

This was achieved by utilizing finer WPA with particle size range 1mm-0.063mm (i.e. WPA type B) for the mix instead of the particle size 4mm-0.125mm (i.e. WPA type A) employed for the previous mixes.

As mentioned in the thesis WPA particle sizes and the Water/binder ratio were the only difference between TM4 and TM3.

APX. 1.5: FINDINGS FROM CWLB PRELIMINARY EXPERIMENTATION

The detail discussion of findings obtain from the preliminary study as summarised in the thesis (Chapter 4, Section 4.9) are presented below.

Apx. 1.5.1 Effectiveness of Waste additive as binder

Binders are substances which are employed to bind inorganic and organic particles and fibres to develop strong, hard or flexible components as the case maybe (Stulz and Mukerji, 1993). For different kinds of binders, the process of binding may occur: chemically, mechanically and/or naturally through drying in the presence of air depending on their types and composition. According to Stulz and Mukerji (1993), hydraulic binders harden and develop strength in the presence of water while non-hydraulic binders harden in the presence of air. Based on literatures, binders can be further grouped into: Mineral binders, Bituminous binders, Natural binders and Synthetic binders (Stulz and Mukerji, 1993). The waste additive (i.e. waste lactose) utilized as binder in the constituent of CWLB being developed in this study can therefore be categorized as a natural binder. Stulz and Mukerji (1993) defined natural binders as a range of binders that are obtained from plants and animals, which can either be applied in their natural form or after processing. For those obtained from animal product, he gave examples like bull's blood; animal glues from horn, bone, hooves and hide; casein or whey made from milk. The same author mentioned the previous use of this group of binder in construction in the olden days and the present importance associated with their use in today's construction due to their cost effectiveness and environmental acceptability.

The findings from the preliminary experimentation showed that the waste additive (waste lactose) employed as binder is compatible with other constituent material of CWLB. As shown in Table Apx. 1.5, TS1 group of CWLB specimen displayed moderate strength at 28 days curing age, which suggests that the binder was able to the hold the constituent materials together**.** Aside this, evaluation of the compressive strength of TS2 specimen containing 0% and 20% binder content by weight of WPA (Fig. Apx. 1.6) shows that in all cases the binder (waste additive) is responsible for 40%, 45%, 37%, 41%, 50%, and 30% of the strength

Table Apx. 1.5: Compressive strength of Trial specimen 1(TS1)

Mix No.	MIX ID	**Load kN**	**Compressive strength (MPa) (at 28 days) (n=3)**
1	M1	2.67	1.07
2	M2	2.56	1.02
3	M3	1.74	0.69
4	M4	1.47	0.59
5	M5	1.2	0.48
6	M6	3.74	1.50
7	M7	3.39	1.35
8	M8	2.18	0.87
9	M9	1.35	0.54
10	M10	0.86	0.34
11	M11	4.83	1.81
12	M12	3.85	1.54
13	M13	3.66	1.46
14	M14	2.59	1.04
15	M15	2.79	1.12

development in specimen containing 0%, 4%, 8%, 12%, 16%, and 20% sand content by weight of WPA respectively. It was therefore decided to continue with the use of waste lactose as the binder in all further experimentation on CWLB.

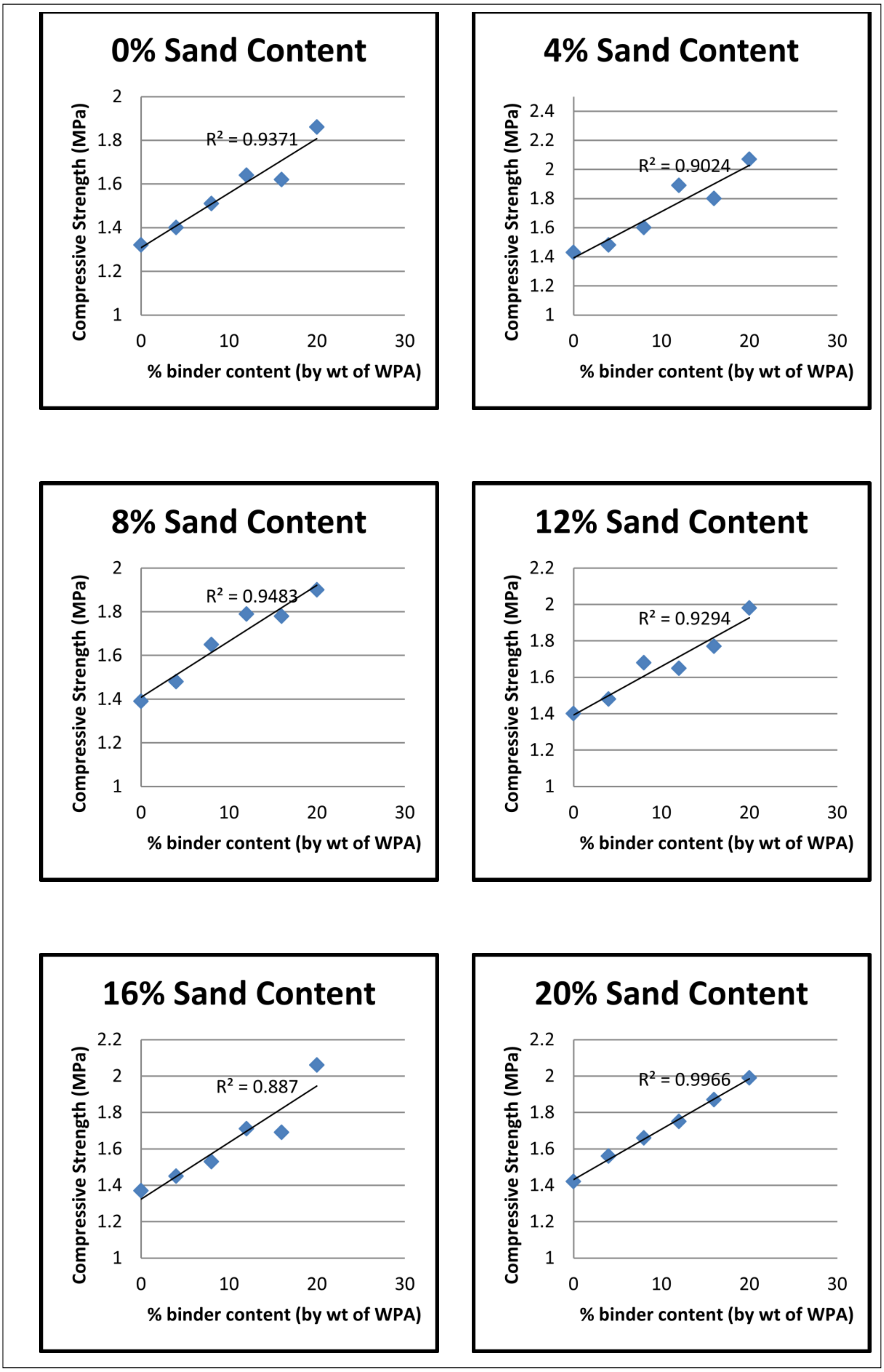

Fig. Apx. 1.6: Effectiveness of waste additive as binder in CWLB

Apx. 1.5.1 Significance of mixing water and Natural admixture in CWLB mixture

The incorporation of mixing water and 5% stoneware clay as an admixture in the CWLB is important to produce a suitable and efficient CWLB mixture. Even though the binder used was in liquid form, the addition of separate mixing water resulted in conservation of the binder used. Aside this, evidence from the literatures shows that building materials containing organic materials like paper/cellulose, wood, paper, paper-faced drywall or carbon-based material, carpeting, or batt insulation have the tendency to exhibit mould growth (PUB08-1192DN17 Designers notebook, 2008) because their organic components may act as food source for such growth , however, further research evidence showed that most fungi/mould cannot thrive at PH below 5 and higher than 8 (i.e. neutral to slightly acidic) For example concrete can control fungal growth due to its pH range of (10 to 13) (PUB08-1192DN17 Designers notebook, 2008). A similar occurrence was observed on CWLB specimen produced from mixtures in which lactose served as both the binder and mixing water in the sense that tiny bit of cleanable mould growth which was believed to have resulted from high level of organic content (i.e cellulose and waste additive) appeared on the surface of the specimen at 28 days curing age. However, the incorporation of adequate mixing water to reduce the content of binder (thereby indirectly reducing the organic concentration) and addition of 5%-10% clay as natural admixture (to raise the PH of the mixture beyond the level at which mould can thrive) (as in TM2 and corresponding TS2) completely eliminated the appearance of mould growth (see Fig. Apx. 1.7). It was therefore decided to incorporate mixing water and 5% clay as natural admixture in the constituent of CWLB in all further experimentation.

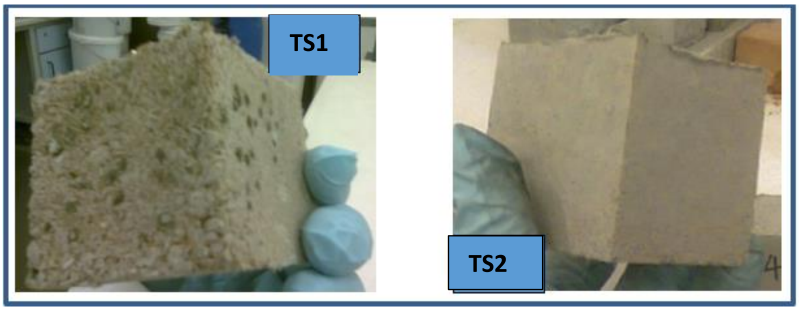

Fig. Apx. 1.7: Appearance of Mould on TS1 and Absence of Mold on TS2

Apx. 1.5.2 Elastic Springback characteristic of CWLB mixture

Biomaterials such as cellulose fibre tend to spring back upon release of densification pressure when they are forced into any physical form due to their limited degree of elasticity (Bruhn *et al.*, 1959 in Mani *et al.*, 2003). This phenomenon of negligible elastic recovery in densified biomass can be corrected through the introduction of stabilizing agents (Mani *et al.*, 2003).

Due to the presence of wastepaper fibres, CWLB mixture exhibits characteristics that are similar to that of densified biomass. The findings from trial experimentation shows that the use of adequate proportion (or ratio) of sand relative to WPA is required and important to produce stabilised and dimensionally stable CWLB specimen. Based on research evidence from the literatures, densified cellulose fibre (e.g briquettes or pellets) compressed in a closed cylinder have the tendency to exhibit longitudinal expansion in the direction of compression as the pressure is released (Olorunisola, 2007). This phenomenon which Dhanodaran and Afzal, (2012) described as a springback effect occurs in compacted fibrous granular/powder material due to the release of elastic energy stored in the fibre during the compaction process. The same author reported further that, thermoplastic materials (like cellulose/wastepaper fibre) react to pressure application either elastically or visco-elastically in the course of compaction. And during the decompacting stage, certain amount of residual stress appears in the form of springback. A similar behaviour was observed during the compaction of CWLB under hydraulic press in that CWLB specimen produced from mixtures containing lower sand content in the range of 0% -32% (by weight of WPA) were susceptible to longitudinal expansion (as in TS3) upon release of pressure during molding.

However, the use of adequate proportion of sand content in the range of 36% - 52% (by weight of WPA) in the mixes produced a more stabilized and acceptable specimen. As shown in (Fig. Apx. 1.8), specimen produced from mixtures containing 0% - 32% sand content displayed higher rebounding in the range of 30% - 10% which is higher than the acceptable dimensional deviation limit for blocks, while the specimen containing 36%-52% sand content displayed lower rebound in the range of 7% - 0.6% which is within the limit of permissible dimensional deviation specified by BS 771-4:2011. Also, the R^2 value of 0.99 displayed by fitted regression line indicated that a strong correlation or relationship exists between these two parameters. It was therefore decided to study mixture containing 36%-52% (by weight of WPA) in all further experimentation.

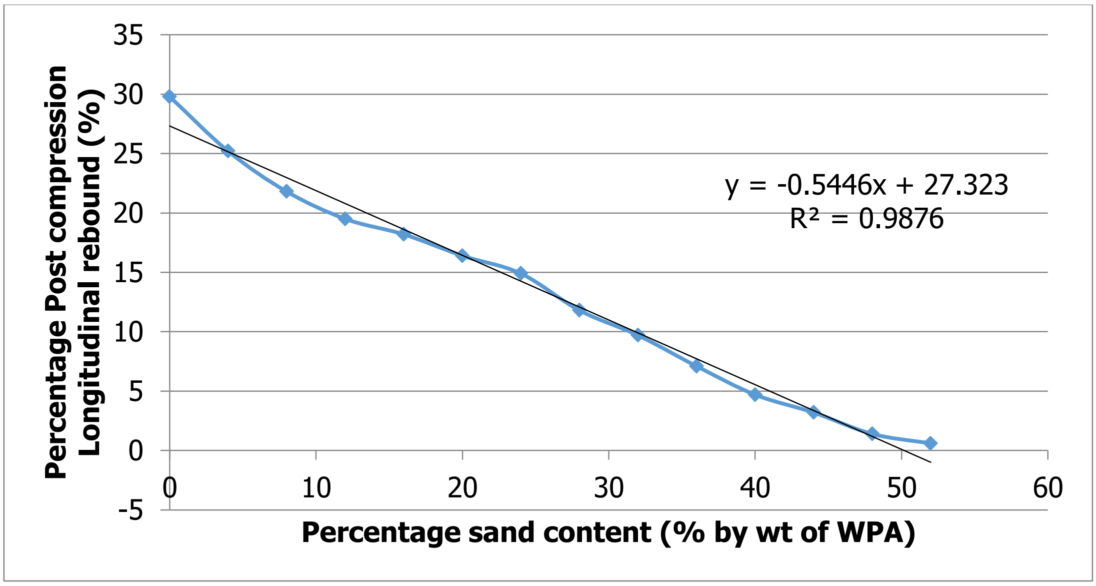

Fig. Apx. 1.8: Effect of sand content on post-compression rebound/springback characteristics of CWLB

APX. 1.6 SIGNIFICANCE OF WPA GRANULATION ON DEGREE OF COMPACTION OF CWLB MIXTURE

The degree of compaction of CWLB specimen depends on the particle size/granulation of the wastepaper aggregate. Based on observation, inadequate compaction and void spaces were noticed on the surface of specimen produces from coarser WPA (4mm-0.125mm) (i.e. WPA–type A) compared to those produced from finer WPA (1mm - 0.063mm) (i.e. WPA-type B). Also, the density comparison presented in (Fig. Apx. 1.9) shows that, despite using the same mold size, the same compacting force, and lower water content, the CWLB specimen (i.e. TS4) produced from the finer WPA exhibited higher weight than that of TS3.This indicates that the particles of WPA along with other constituents of the mixture were more tightly packed together (i.e. highly compacted) in TS4 than in TS3. It was therefore inferred that the finer WPA produces a more highly compacted CWLB specimen compared to the coarser particle. This finding comes in line with the submission of research evidence regarding the compaction of fibrous material which revealed that the density and durability of densified/compressed cellulose fibre is inversely proportional to the particle size because the smaller particles have greater surface area contact during compaction (Tumuluru *et al.*, 2010).

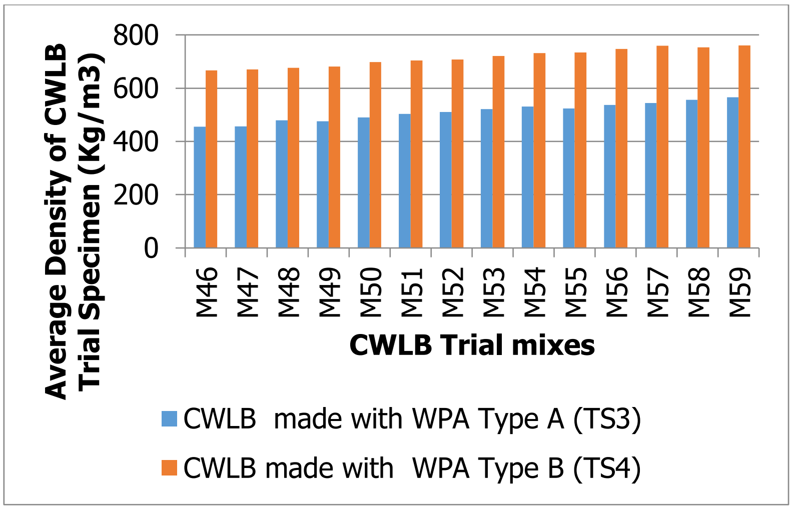

Fig. Apx. 1.9: Effect of WPA granulation on degree of compaction of CWLB

However, in order to sustain the eco-friendliness of the processing of CWLB, a medium WPA particle size (i.e. WPA type C (with particle passing BS sieve 3.35 mm)) produced from sieving/screening of the (WPA type A) coarser particle size was considered for use instead of the finer WPA particles sizes (WPA type B) previously produced through milling. Based on the recommendation by Payne (1997) which states that to produce good quality densified specimen (e.g pellets) from cellulose fibre, the granulation of the material should be such that the material retained on sieve 3.0 mm should be less than or equal to 1%, while those retained on sieve sizes below 0.25 should be greater than or equal to 20%. This indicates the need for the material to contain more percentage of finer particles. Based on simple screening experimentation conducted on WPA, It was decided to utilize WPA particle passing 3.35 mm BS sieve size (WPA Type C) in all further experimentation since its particle granulation closely agrees with the Payne (1997) recommendation. In order to further ascertain the suitability of WPA Type C for the intended function, and the density and compressive strength of CWLB specimen produced using the each of WPA type A, B and C were compared as shown in (Fig. Apx. 1.10 and Fig. Apx. 1.11).

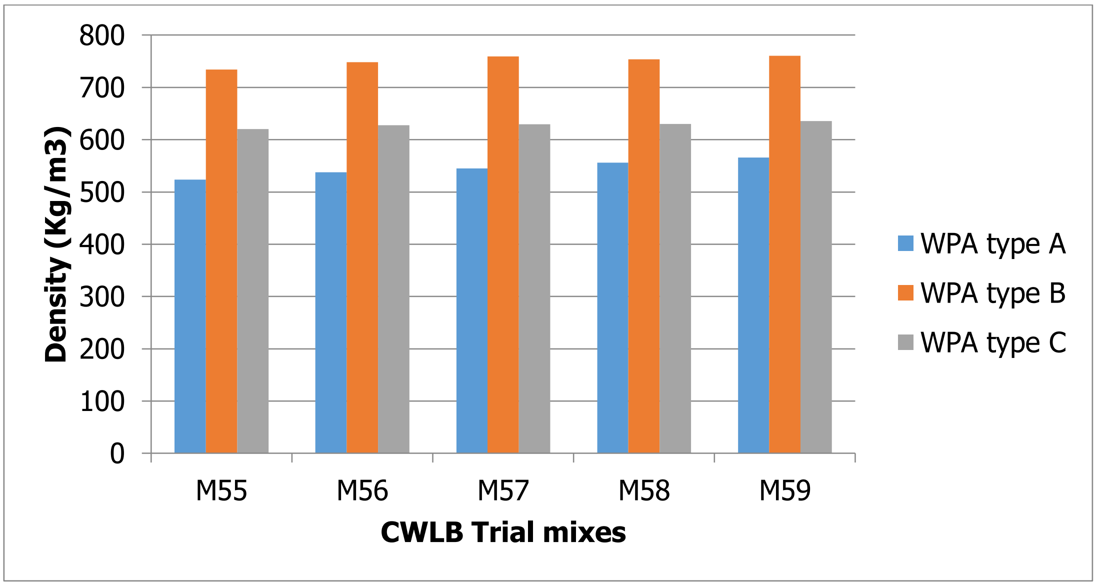

Fig. Apx. 1.10: Density of CWLB produced from varied WPA granulation

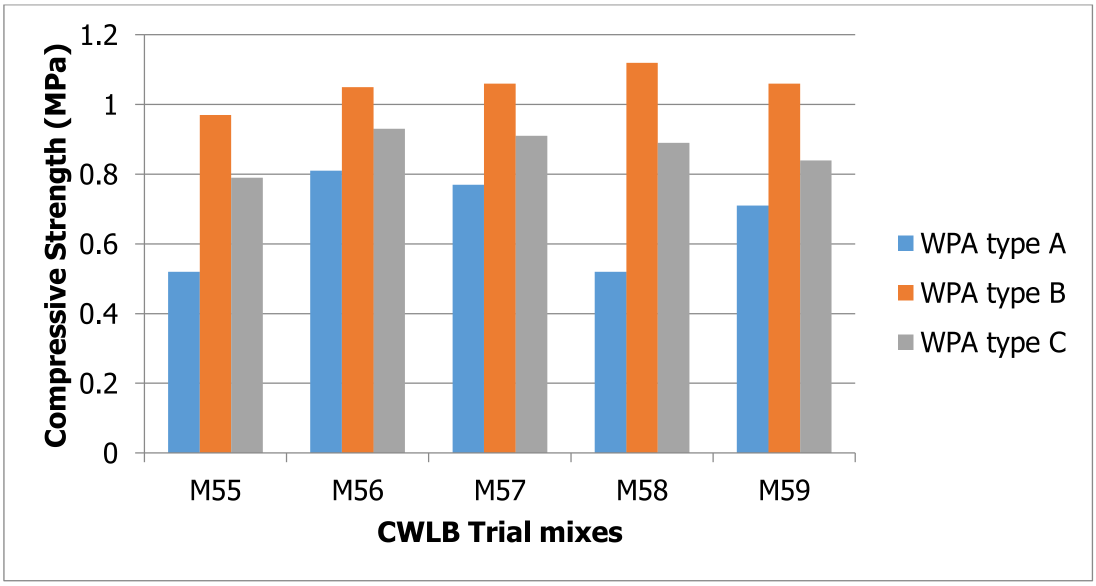

Fig. Apx. 1.11: Compressive strength of CWLB produced from varied WPA granulation

A shown in (Fig. Apx. 1.10 and 1.11), it was found that in all cases, specimen produced using WPA type C displayed more than 10% increase in density and compressive strength relative to specimen produced from WPA type A. Also, the minimal processing required for WPA-type C made it a more sustainable option compared to WPA type B. The findings indicated that using WPA type C brought about high degree of compaction and an attendant higher strength in the resulting CWLB specimen thereby ascertaining the suitability of WPA type C particle granulation for the intended application, therefore, the earlier decision was sustained.

APX. 1.7 SIGNIFICANCE OF WPA GRANULATION ON MIXING WATER REQUIREMENT OF CWLB MIXTURE

Also, the bigger the particle size of WPA, the higher the mixing water requirement for CWLB mixture and the smaller/finer the particle sizes the lesser the mixing water requirement. This phenomenon is probably due to water repelling properties that cellulose fibre is said to exhibit at microscopic level, according to (Immergnt,1975 cited in Olorunisola, 2007), at microscopic level, cellulose fibre contains waxes (water repellants) along with other non-cellulosic substance. Observation during experimentation shows that the use of WPA type B (with 1mm-0.063mm particle size) enabled the utilization of 75% water content (by weight of WPA) for mixing compared to the previous trial mixes in which workable mixes were obtained at 200% water content (by weight of WPA). This indicates that the utilization of finer WPA brought about 125% reductions in water content requirement for the workability of CWLB mixture. This observation further indicated the need to study the effect of water content on the compressive strength of CWLB and the need to adopt the use of less coarsed WPA in all further experimentation.

APPENDIX 2: ECO FRIENDLINESS OF CWLB COMPARED TO PAPERCRETE

APX. 2.1 ECO FRIENDLINESS OF CWLB COMPARED TO PAPERCRETE

Considering the high amount of waste content which for the five CWLB mix categories ranged from 70%-77% (Table Apx. 2.1), CWLB can be regarded as being highly eco-friendly in terms of conservation of natural resources and reduction of GHG due to the non-use of hydraulic binder. As shown in Fig. Apx. 2.1, Eco Friendliness of CWLB in terms of constituent materials can be highlighted as:

- 75% waste content indicate natural resources conservation and reduced environmental pollution
- 0% cement indicate reduction in greenhouse gas emission(GHG) such as CO_2, and indirect reduction in energy consumption
- Use of Waste by-product as waste additive implies the practice of industrial ecology

Table Apx. 2.1: Mix composition and eco friendliness of CWLB

Min no	Mix ratio P : S : B	%WPA	%Sand	%binder	Total Waste content (WPA+binder) (%)
	1:0.36:0.20	64.1	23.1	12.8	77
	1:0.40:0.20	62.5	25	12.5	75
	1:0.44:0.20	61.0	26.8	12.2	73.
	1:0.48:0.20	59.5	28.6	11.9	71.
	1:0.52:0.20	58.1	30.2	11.6	70

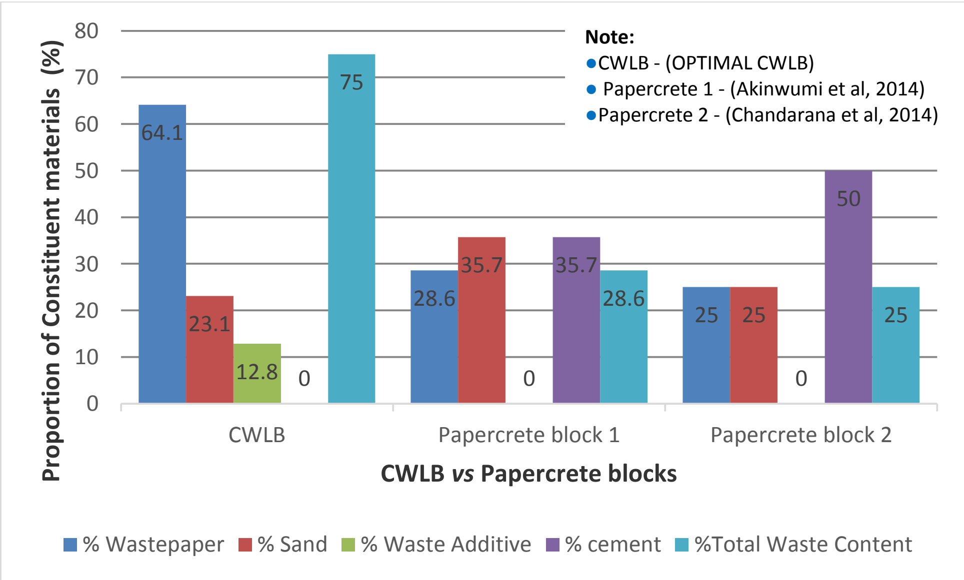

Fig. Apx. 2.1: Eco-friendliness of CWLB versus Papercrete blocks, in terms of constituent materials

APPENDIX 3: FUNDAMENTALS OF SIMULATION MODELLING

APX. 3.1 SIMULATION MODELLING

Simulation modelling is a process of creating and analysing a digital prototype of a physical model to predict its performance in the real world (Sanchez, 2007). It usages assist engineers and designers to find out how a part or product will behave in real life application. It provide means of understanding whether such product will fail or otherwise under certain conditions. Aside from its use in structural investigations (e.g. for determination of loads that can be withstood by a part), it is also commonly employed in fluid and heat transfer problems.

Apx. 3.1.1 Benefit of Simulation Modelling in Development of new Product

Simulation modelling enable designers and engineers to prevent the need for repeated creation of multiple physical prototypes of a product for the purpose of analysing the design for new or existing parts. It helps to investigate digital prototype of a product without the having to physically create them. Depending on what the product is and its intended application, literatures (Robinson, 2014; Banks *et al.*, 2010) reported that the implementation of simulation modelling can help to achieve the following:

- Optimize geometry for weight and strength.
- Select materials that meet weight, strength and budget requirements.
- Simulate part failure and identify the loading conditions that produces them
- Assess extreme environmental conditions or load not easily tested on physical prototypes

- Verify hand calculation
- Validate the likely safety and survival of a physical prototype

Apx. 3.1.2 Types of Modelling Simulation

The various types of modelling method commonly employ in modelling and simulation as reported by literatures (Banks *et al.*, 2010; Sokolowski and Banks, 2009a; Sokolowski and Banks, 2009b) includes:

- Physical based modelling – Mathematical model in which model equations are derived from basic physical principles
- Finite Element Modelling- Decomposition of a large object into a set of smaller objects labelled elements
- Data-Based Modelling- Data describing represented aspects of the subject of the model
- Agent -Based Modelling- For investigating many types of human and social phenomenon
- Aggregate Modelling- A number of smaller objects and actions represented in a combined manner
- Hybrid Modelling- Combination of more than one modelling method

Further classification includes; live, virtual and constructive modelling. Live simulation involves real people operating real system or equipment. Virtual simulation involves real people operating in simulated systems. Constructive simulation involves real people making inputs into a simulation that carry out those inputs by simulated people operating in simulated systems.

APX. 3.2 FUNDAMENTALS OF FINITE ELEMENT SIMULATION MODELLING

Basically, the finite element method of simulation involves the discretization of the actual geometry of a physical problem using a cluster of finite elements. The physical problem could be a structure, building component (e.g. block unit, beam, truss, column etc.), parts or system as the case may be. An individual finite element stands for a discrete portion of the physical problem and the group of finite elements are connected to each other by nodes. The assembly of the nodes and the Finite elements is usually referred to as mesh. The number of elements present in a unit of length, area or in a mesh represents the mesh density. In a stress analysis such as the one being conducted on CWLB, the fundamental variable that simulation software calculates is the displacement of the nodes. The acquisition of this nodal displacement enables the determination of the internal forces, external forces, stresses and strains in each of the finite elements depending on the boundary conditions prescribed (Abaqus 6.13 online documentation, 2013c)

Though FE simulation modelling can be performed using different softwares including; Abaqus CAE, ANSYS, Simio, Anylogic, Autodesk simulation mechanical, Matlab etc., the basic principles and the processes involved in carrying it out remains the same. According to Banks *et al.* (2010), the generic stepwise approaches for carrying out simulation modelling using softwares includes;

1) The use of a 2D or 3D CAD tool to develop a virtual model (i.e digital prototype) to represent a design.

2) The generation of a 2D or 3D mesh for analysis calculations Such as finite element meshes can be created through the use of automatic algorithms or user self-created structured meshes (in cases where element control is required)

3) Definition of finite element analysis data (e.g. loads, constraints, displacements, or material properties) depending on the type of analysis employed (stress, thermal, structural or fluid). At this stage, boundary conditions are applied to the model to represent how the part will be restrained during use.

4) Performance of the finite element analysis, review, and evaluation of results obtained and formulation of engineering judgement based on the results.

APX. 3.3 WHAT IS ABAQUS CAE?

Abaqus CAE (also known as; Complete Abaqus Environment) is a finite element modelling and simulation software that contains an extensive library of elements suitable for modelling of different types of geometry. It incorporates varieties of material model that enable the user to simulate the behaviour of lots of typical engineering materials. Some of such materials include; metal, rubber, polymer, composites, reinforces concrete, crushable and resilient foams and geotechnical materials like soils and rocks. It simulation capabilities can be used to simulate many engineering problems including; structural (such as; stress or displacement), heat transfer, mass diffusion, thermal management of electrical components (e.g. coupled and thermal electrical analysis), acoustics, soil mechanisms (e.g. couple pore fluid stress analysis and piezoelectric analysis)

APX. 3.4 : MESH DENSITY AND MODEL ASSEMBLY FOR CWLB MODEL GEOMETRIES

Table Apx. 3.1: Mesh Density for The Model Assembly for The Model Geometries

Meshing Parameter	**Model assembly for cube block**			**Model assembly for Solid block**			**Model assembly for hollow block**		
	Top plate	**Cube block**	**Lower plate**	**Top plate**	**Solid block**	**Lower plate**	**Top plate**	**Hollow block**	**Lower plate**
Element type	R3D4	C3D8R	R3D4	R3D4	C3D8R	R3D4	R3D4	C3D8R	R3D4
Number of Elements (Mesh density)	16	2197	16	27	2304	27	27	2262	27
Number of nodes	25	2744	25	41	2925	41	41	3178	41